

**Memorandum**

Date : September 23, 1994

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Subject : Sacramento River Bank Erosion Investigation Memorandum Progress Report

The Department of Water Resources, Northern District, began the *Sacramento River Bank Erosion Investigation* to collect data on significant river geomorphic characteristics such as erosion, deposition, and meandering in the 100-mile reach between Red Bluff and Colusa. The study also considers long-range geomorphic changes caused by such human activities as dam construction, bank protection, and gravel mining.

These data are used by the Department of Water Resources and other agencies in addressing present and future significant issues, such as water projects, fish and wildlife, loss of wetlands and agricultural land. These data may be used to resolve land-use conflicts and develop a management plan.

The study consists of bank erosion, floodplain deposition, river channel changes, and Lake Red Bluff changes.

Our bank erosion study was divided into two phases. The Phase Aerial Photography Bank Erosion Study identified 67 eroding bank sites between Red Bluff and Ord Ferry. We measured the amount of erosion and sediment production at these sites over a 10-year period using aerial photography. In the Phase II-Bank Erosion Monitoring Sites Study, we surveyed 15 eroding bank sites between Red Bluff and Colusa. These have been resurveyed biannually since 1986.

Floodplain deposition was measured by resurveying cross-sections originally surveyed by the U. S. Corps of Engineers in the 1920s and the U. S. Geological Survey in the 1970s and 1980s. The cross-sections were compared and the amount of deposition or erosion measured.

We resurveyed U. S. Bureau of Reclamation cross-sections in Lake Red Bluff, U. S. Geological Survey cross-sections at stream gages, and measured river depths and widths to determine long-term changes.

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## **PART I: INTRODUCTION**

**INTRODUCTION  
SUMMARY AND CONCLUSIONS  
RECOMMENDATIONS**

## INTRODUCTION

One of the more interesting parts of the State is the Great Central Valley that occupies the central region. The southern end of this valley is called the San Joaquin Valley, and the northern part is called the Sacramento Valley, named after the rivers that run through them. The Sacramento River headwaters are on the east slope of Mt. Eddy in the vicinity of Mt. Shasta. The town of Mt. Shasta is known for being the city of pure water. From Mt. Shasta the river is cradled between the Cascade Range on the east and the Klamath Mountains on the west. The river then enters the Great Central Valley near Redding, flows through the Sacramento Valley and empties into the San Francisco Bay. The Sacramento Valley is approximately 150 miles long and from 30 to 60 miles wide. The elevation varies from 10 feet below sea level in the Sacramento-San Joaquin Delta region to about an elevation of 500 feet at the extremities. It is bordered on the east by the Sierra Nevada and Cascade Ranges, and on the west by the California Coast Ranges.

The Sacramento River is the largest and most important river system in California. It drains 17 percent of California's land area, yet yields 18.4 million acre-feet, or 35 percent of the water supply. The river is the State's most important salmon resource. The riparian corridor between Red Bluff and Colusa is one of the richest and most diverse wildlife habitats remaining in California.

About 150 years ago, the Sacramento River was bordered by up to 500,000 acres of riparian forest, with bands of vegetation spreading 4 to 5 miles. Less than five percent of the original acreage remains today (Resources Agency, 1989). In 1979 the U.S. Fish and Wildlife Service reported that 95 percent of the stream miles of salmon and steelhead habitat in the state was lost, as well as 91 percent of the natural wetlands used by migratory birds (Sudman, 1980). Today more than 65 major dams plug canyons and ravines on the Sacramento and its tributaries (Mayer, 1989).

Bank erosion is an active, natural process in the Red Bluff to Colusa study reach. It generally occurs on the outside of meander bends. Here, banks are susceptible to erosion because high-flow velocities impinge directly onto banks. The eroding banks typically consist of sand and silt underlain by sand and gravel. Over time, the river meanders across the floodplain by eroding one bank and depositing sediment on the other. The fish, wildlife, and riparian vegetation are adjusted to the cycle of erosion, deposition, and changing channel pattern in which the river swings slowly back and forth across the meander belt. The health and productivity of the system at any one point is dependent on the periodic rejuvenation associated with these changes.

The Sacramento River's geology, geomorphology, and hydrology have combined to produce a unique riparian habitat that supports a varied wildlife. In the past, the Sacramento River meandered freely across its floodplain, eroding high terrace lands and replacing them with low terrace gravels. Over time, sediment deposition would eventually convert these low terrace

gravels back to high terrace land. This natural erosional-depositional cycle supported a unique riverine ecology adapted to these fluctuating processes.

Human-induced changes to the Sacramento River, including bank protection, gravel mining, pollution, riparian vegetation removal, flow regulation, and flood control, have resulted in a number of physical and ecological effects. This study focuses on changes in bank erosion, bank composition, river length, depth, width, sinuosity, and floodplain deposition.

DWR has been monitoring these changes using old survey maps, aerial photographs, and field surveys. Completed studies indicate that bank protection has significantly reduced a source of salmon spawning gravel from freshly eroded banks and will over time decrease the number of preferred spawning areas such as point bar riffles, chute cutoffs, multiple channel areas, and areas near islands. Bank protection also increases the tendency of the confined river to deepen and narrow, further reducing spawning habitat. Because of flood protection from dams and extensive bank protection along eroding banks, most of the rich high terrace soils and all but a small percentage of the original riparian forest has been converted to agriculture and other uses. In addition, only 45 percent of the original streambank vegetation remains.

Wildlife populations have declined markedly due to loss of riparian habitat and suppression of the natural successional processes that maintain the density and diversity of habitat within the riverine environment. Some species that are adapted to the dynamics of the erosional-depositional cycle are threatened with extinction or extirpation as key habitat elements are lost from the newly stabilized river system. Flood control has interrupted the natural equilibrium between erosion and deposition, resulting in reduction in bank erosion rates and in overbank sediment deposition.

Bank erosion has been a serious problem for farmers along the banks of the river. The river meander zone varies from about 500 feet to over 7000 feet depending on the location. Valuable cropland and orchards are routinely lost. Campgrounds, roads, levees and bridges are also at risk. The east bank at Woodson Bridge State Recreation area receded over 45 feet in a single storm, resulting in the loss of a road and other park facilities.

## **Purpose and Scope**

The purpose of the *Sacramento River Bank Erosion Investigation* is to collect data on significant river geomorphic characteristics such as erosion, deposition, and meandering. DWR and other agencies use these data in addressing present and future significant issues, such as water projects, fish and wildlife, wetlands, loss of agricultural land and others. These data will be used to resolve land-use conflicts and develop a management plan.

Shasta Dam was completed on the Sacramento River north of Redding in 1945. The dam eliminated access to a large portion of the traditional salmon spawning habitat. It has had major effects on the distribution of streamflow, resulting in geomorphic adjustments in bank erosion rates, river meander rates, and sediment deposition.

There are a number of concerns relating to the construction of Shasta Dam and proposals for future water storage and conveyance. Foremost amongst these is the effect of these projects on bank erosion along the Sacramento River. Erosion has caused the loss of prime agricultural land, but has also contributed up to 85 percent of the spawning gravel that salmon require (DWR, 1984). Also, there is a need to analyze baseline geomorphic data to quantify the complex relationships between bank erosion rates and flows, bank composition, channel geometry, and riparian vegetation. The long range use for these analyses includes:

- Providing the basic data required for development of an effective Sacramento River management plan.
- Studying the relations between bank erosion and other river processes such as riparian succession, wetlands formation, and spawning gravel recruitment.
- Reducing damage caused by present water management practices.
- Assessing the effects of human impacts, such as riprapping, gravel mining, agriculture, and diversions on the river system geomorphology. These changes in channel dynamics affect the unique riparian ecology that has evolved along the river. Some riverine species are listed as rare or endangered, or are pending listing.

The Department of Water Resources, Northern District, began this Sacramento River geomorphic study in 1986. The study consists of bank composition, bank erosion, floodplain changes, channel changes and Lake Red Bluff changes. The study also considers long-range geomorphic changes caused by such human activities as dams, bank protection, and gravel mining. Geomorphic changes include channel narrowing and deepening; changes in riparian vegetation, channel length, width, sinuosity, bank erosion and sediment transport rates.

In the Phase I "Composition of Eroding Banks" study, 67 eroding banks were identified between Red Bluff and Ord Ferry using aerial photography. We measured the amount of bank erosion and calculated the erosion rates and the amount and size of sediment introduced to the river at each site.

In the Phase II "Bank Erosion Monitoring Sites" study, ten bank erosion monitoring sites were surveyed in 1986 in the 58-mile study reach between Red Bluff and Colusa. An additional six sites were surveyed in 1988. The sites are resurveyed semi-annually. Each site was mapped and a plate prepared showing the geology, vegetation, hydrology and bank erosion for the period of record.

Floodplain deposition was also monitored. Deposition is the regenerative process which rebuilds the floodplain destroyed by erosion. Ten floodplain cross-sections were surveyed to monitor sediment deposition and long-term changes.



Cross-sections surveyed by the U.S. Bureau of Reclamation in Lake Red Bluff were resurveyed to determine historic changes. The purpose of this part of the study was to determine sediment transport in this part of the study area.

Cross-sections surveyed at various times by DWR at gaging stations were also compared. Changes in the cross-sectional areas were tabulated to determine long-range trends.

## Previous Studies

Bank erosion was monitored as part of the *Observations of Sacramento River Bank Erosion, 1977-1979* (DWR, 1979). For two years, six active bank erosion sites were monitored periodically to document bank recession. A report was published in 1979 outlining the results.

The report concluded that erosion potential and appearance of any given site changed after each storm. During the life of an eroding bank, two identical flows will produce different amounts of bank erosion. The study also concluded that there is no fixed correlation between flow and erosion for a specific site.

Monitoring of four of the six sites was continued until 1983. The memorandum report, *Effect of Enlarged Shasta Reservoir on Sacramento River Bank Erosion* (DWR, 1985) presented the results of this study. The study correlated Sacramento River bank erosion with three parameters: the volume of flow between erosion measurements, the peak discharge, and the average daily discharge. In general, the correlation ranged from good to poor, depending on the erosion site and the correlation parameters.

The study concluded that a reduction in bank erosion would occur from the operation of Enlarged Shasta; an average annual reduction of as much as 20 percent would occur in certain river reaches; and winter erosion would be greatly reduced while summer erosion would be slightly increased. Other conclusions reached include:

- The reach of the river between Hamilton City and Colusa is the most erodible;
- Low flow erosion can occur from mechanisms unrelated to flow, such as rainfall, poor irrigation practices, or high water tables;
- High flow erosion typically occurs when high flows dislodges soil particles and undermine the banks;
- Of three correlation parameters, bank erosion correlated best with peak discharge;
- The erosion rates varied greatly between erosion sites, with the Princeton site the highest.

DWR has published a number of related reports on the Sacramento River. These include: *Woodson Bridge State Recreation Area Erosion Study* (1979), *Upper Sacramento River Spawning Gravel Study* (1980), *Middle Sacramento River Spawning Gravel Study* (1984), and the *Sacramento River Spawning Gravel Studies - Executive Summary* (1985). These three reports discuss Sacramento River morphology. The atlas appendices delineate the extent of the Sacramento River meander belt. The reports *Land Use Changes in the Sacramento River Riparian Zone, Redding to Colusa, A Second Update - 1977 to 1982* (1983), and *Land Use Changes in the Sacramento River Riparian Zone, Redding to Colusa, A Third Update - 1982 to 1987* (1987), provide details on changes in land use and riparian vegetation.

The two sources of regional information available for this area are the U.S. Geological Survey Red Bluff geologic map sheet (USGS, 1984) and the U.S. Soil Conservation Service county soils descriptions (SCS, 1967).

Site specific reports include the U.S. Bureau of Reclamation's investigation of the backwater effects of the Red Bluff Diversion Dam (USBR, 1970, 1985).

## **Location and Access**

The focus of this investigation is on the 100-mile reach of the middle Sacramento River between Red Bluff and Colusa (Figure 1). This reach is identified as having the greatest amount of bank erosion along the entire river. The study area includes the tributary watersheds in this reach because of their influence on natural and human-induced processes.

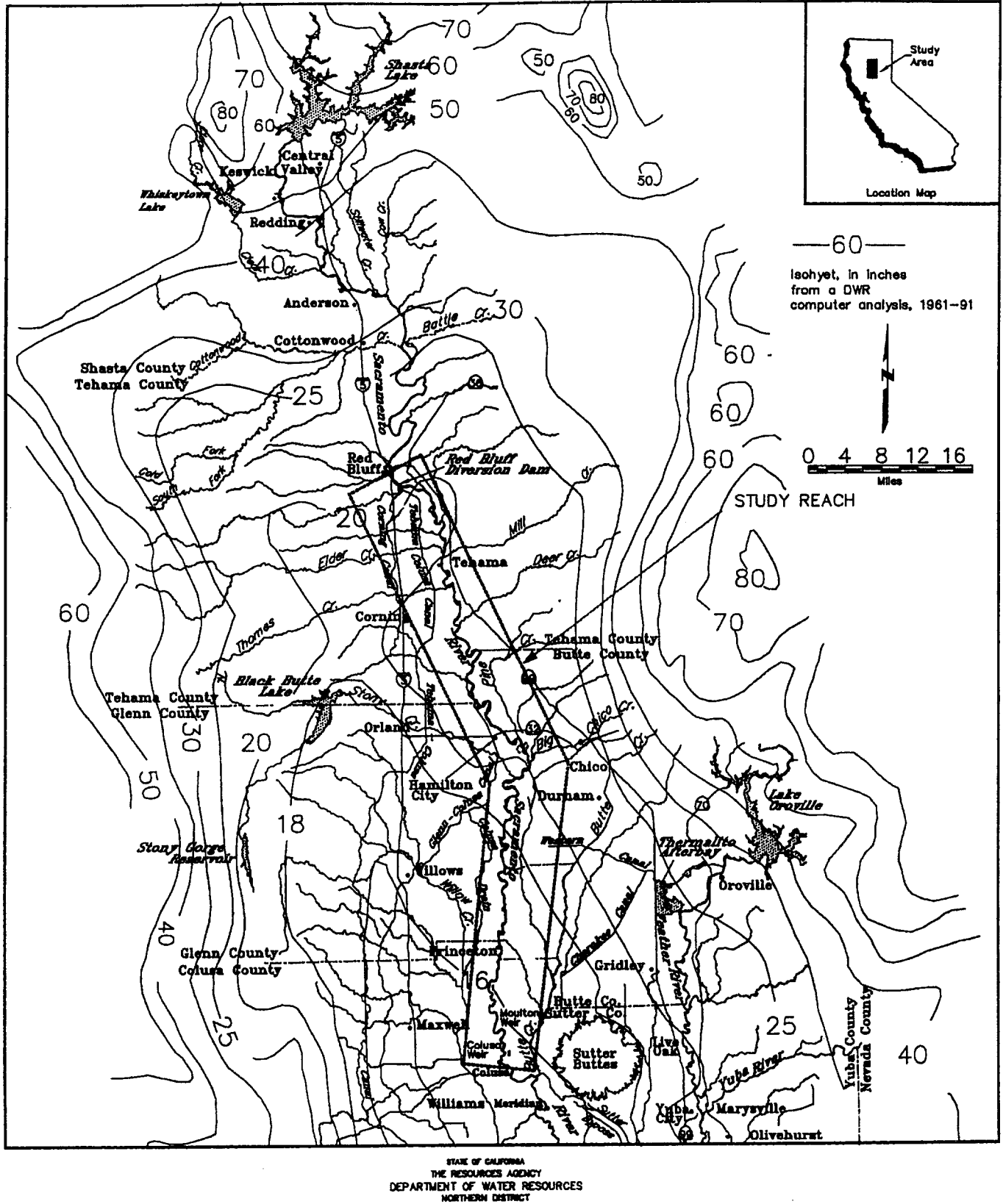
Towns in the reach include Red Bluff, Hamilton City, Butte City, Princeton and Colusa. The reach is navigable with small craft such as canoes and rafts and jet boats. During the late fall low flows, some of the riffles are difficult to navigate.

Most of the reach between Red Bluff and Hamilton City is private and lacks public access except at the City of Tehama and at Woodson Bridge. From Hamilton City to Colusa, State Highway 45 roughly parallels the course of the river and provides access in a number of places. Public boatramps are located at Red Bluff, Tehama, Woodson Bridge, Hamilton City, Ord Ferry, Butte City and Colusa. Additional access is available at private resorts in a number of places.

## **Climate and Streamflow**

The Sacramento Valley has a Mediterranean type climate with hot, dry summers and cool, wet winters. Topography significantly influences both temperature and precipitation. The average annual temperature ranges from about 60 degrees Fahrenheit in the valley to 40 degrees in the mountains.

Figure 2



Sacramento River Bank Erosion Investigation  
Isohyetal Map  
Sacramento River from Red Bluff to Colusa

The Sacramento River discharge has been further modified by diversions on the river and tributaries. Three major diversions exist between Red Bluff and Colusa, diverting water for agricultural irrigation. These are the Red Bluff Diversion Dam, the Glenn-Colusa irrigation canal, and the River Branch canal at Sidd's Landing near Princeton. Numerous minor diversions and pumps also exist along the river.

A number of tributaries enter the Sacramento River along the study reach. Some of these tributaries also have diversions that divert water for agricultural irrigation. These diversions reduce discharge to the river, reduce downstream spawning gravel recruitment, and may impede fall runs of spawning salmon.

## Vegetation

The northern Sacramento Valley was first settled by Americans in 1844 with grants obtained from the Mexican government. The area was heavily forested at the time, with evergreen conifers in the mountains to the east and west, and oak woodlands in the rolling foothills, and a mixture of valley oak, sycamore, cottonwood, black walnut and other riparian vegetation along streams. Most of the valley riparian woodland has been converted to row crops, orchards or urban development. The blue oak woodland of the foothills has been used primarily for livestock grazing and firewood harvesting.

Vegetative types in the study reach between Red Bluff and Colusa include floodplain riparian forests, blue oak woodland, live oak riparian woodland, grassland and savannah.

### Floodplain Riparian Woodland

Floodplain riparian woodland occurs on the rich soils of the Sacramento Valley floodplain. Most of the river in the study reach lies within this vegetative unit. Valley oak (*Quercus lobata*) is the predominant oak, with sycamore (*Platanus racemosa*), cottonwood (*Populus fremontii*), black walnut (*Juglans nigra*), box elder (*Acer negundo*) and willow (*Salix spp.*) being the other common tree species. Brush species include poison oak (*Toxicodendron diversilobum*), wild blackberry and grape.

Establishment of riparian vegetation occurs sequentially over time as one plant community replaces another. This plant succession is driven by the processes of erosion and deposition. The sequence begins when cottonwood and willow seeds germinate at the waters edge of a newly formed gravel bar. As the river meanders, successive bands of younger trees form, resulting in a gallery forest with many ages and stages of riparian growth. Sand and silt deposit over time, reducing the availability of subsurface moisture. Within the first ten years, sycamore, bow elder, and other species tolerant of dry and shady conditions are established. Black walnut and Oregon ash begin to appear as the cottonwood forests mature. As the cottonwoods age and

begin to die out, a climax forest of valley oaks may become established (Resources Agency, 1989)

The floodplain riparian woodland is naturally a mosaic of habitat types of different ages, species compositions, and vegetative structures that are continually renewed. For this to occur, however, the natural erosion-deposition-regrowth cycle must be allowed sufficient width and time.

### Blue Oak Woodland

The blue oak community forms a nearly continuous ring around the Central Valley of California, generally between 300 and 1000 feet elevation. It is essentially a two-layered community. This community occurs in a few places along the Sacramento River where the river impinges directly on older geologic units such as terrace deposits or the Tehama and Red Bluff Formations.

The major vegetative type is the blue oak woodland (Quercus douglasii). Some individual live oak (Quercus wislizenii) and valley oak (Quercus lobata) may be interspersed. Poison oak is the predominant shrub. Under natural conditions, the blue oak woodland grades gradually into grassland where the soils, slope, and aspect limit tree growth. Blue oak can occupy sites receiving as little as 10 inches of precipitation annually (DeLasaux and Pillsbury, 1987).

Oak woodland occurs on moderately rich, loamy, well-drained soils with neutral or slightly basic pH. Topography is often gently rolling to steep. Oak woodland often occurs in a mosaic with grassland, savannah and chaparral-- a mosaic that reflects differences in slope, aspect, elevation, soil depth, oak harvesting and frequency of fire more than differences in climate (Barbour, 1987).

The present distribution and density of blue oak woodland reflect the effects of land conversion. Major areas that have been converted to grassland and upland agriculture are readily discernible by differences in canopy density and distribution, abrupt straight-line boundaries along section and property lines, and other obvious anomalies. It is estimated that more than 50 percent of the original blue oak woodland has been converted to grazing land or farmland.

### Live Oak Riparian Woodland

The live oak riparian woodland is rare. Major plants include live oak, sycamore, California buckeye (Aesculus californica), cottonwood, and willow. The predominant shrubs are poison oak and wild blackberry. This forest type is most commonly found near the major tributary drainage channels since most of these species have a high water requirement.

### Open Grassland and Savannah

Open grassland and savannah generally has five percent or less blue oak canopy cover but may range to as high as 10 percent. A large part of the western Sacramento Valley area is now open grassland consisting of annual and perennial grasses and forbs. Most of the grasslands outside of

the Sacramento River flood zone were probably originally blue oak woodland converted to grassland by oak harvesting. Wildfires may have created patches of open grassland and mixed-age stands of blue oak, live oak and brush. The current major land use in these areas is seasonal grazing with some dryland farming.

### Chaparral

Brushland does not occur in the valley but in foothill areas with shallow soils too low and dry to support timber. Species common to the area include manzanita (Arotostaphylus sp.), deerbrush (Ceanothus integerrimus), mountain whitethorn (Ceanothus cordulatus), buckeye, poison oak and digger pine (Pinus sabiniana). A broad chaparral belt extends along the foothills from Thomes, northwest through the upper Red Bank Creek and South Fork

Cottonwood Creek basins. A similar but less continuous belt extends along the valley's east side.

### Fir-Pine Forest

Evergreen forests occur in the upper elevations. Principal commercial conifers are ponderosa pine (Pinus ponderosa), sugar pine (Pinus Lambertiana), Jeffrey pine (Pinus Jeffreyi), Douglas-fir (Pseudotsuga menziesii), white fir (Abies concolor), red fir (Abies magnifica) and incense cedar (Librocedrus decurrens). Much of the forests have been selectively cut and some have been clearcut.

### Cultivated

Large areas have been cultivated both periodically and permanently during the last 100 years. Alfalfa, winter wheat, oat, hay, and other forage types are the major crops grown. Most of the dryland farming occurs along the flat-bottomed valleys of Sacramento River tributaries. Most of the irrigated acreage occurs along the Sacramento River, in the lower part of the Sacramento Valley, and on terraces along the lower part of the major tributaries.

## GEOLOGY AND GEOMORPHOLOGY

The study area lies in one of the more interesting parts of the State, the Great Valley geomorphic province that occupies the State's central region. The southern end of this valley is called the San Joaquin, after the river that flows through it. Likewise the northern part of the valley is called the Sacramento valley. The Sacramento River headwaters in the vicinity of Mt. Shasta on the eastern slope of Mt. Eddy. From Mt. Shasta the river flows along the boundary of the Klamath Mountains and the Cascade Range, then down the Sacramento Valley and into San Francisco Bay. The valley is approximately 400 miles long and from 30 to 60 miles wide. The elevation varies from more than 10 feet below sea level in the Sacramento-San Joaquin Delta region to about 500 feet in the north. It is bordered on the east by the Sierra Nevada and Cascade Ranges, on the north by the Klamath Mountains and on the west by the California Coast Ranges (Figure 3).

The Klamath Mountains province is the oldest province, ranging in age from early Paleozoic to Jurassic. The Klamath Mountains province covers an area about 70 miles wide, extending from north of the study area into Oregon. In general, the province consists of several well-defined mountain ranges, including the Trinity, Marble, Scott, and Salmon mountains. These mountains comprise a series of northwest-trending metamorphic terranes separated by major faults. Each terrane differs in age, stratigraphy, and tectonic deformation. Large bodies of intrusive rocks, such as the Shasta Bally batholith, occur throughout the province.

The Sierra Nevada is about 400 miles long, and terminates to the north near Mount Lassen. The rocks of the province are of diverse composition and age, but consist mostly of igneous and metamorphic units. Structurally and tectonically, the Sierra Nevada region is very complex. Some structural deformation dates back 300 million years or more, and is attributed to Paleozoic and Mesozoic subduction.

The Cascade Range is a 500-mile long sequence of volcanoes extending from Mount Lassen to Mount Garibaldi in British Columbia. Rocks of the California Cascade Range are predominately volcanic rocks of great variety and form. In northern California, Upper Cretaceous and Eocene sedimentary rocks are at the base of the sequence. These are overlapped by Upper Eocene volcanic rocks of the Western Cascade series and Quaternary-Tertiary pyroclastic rocks and flows. Near Mount Lassen, the Upper Pliocene Tuscan Formation rests directly on Cretaceous and Eocene sedimentary rocks.

Tectonically, the Cascade volcanoes are the product of the active subduction of the Gorda plate (California), and the Juan de Fuca or Cascadia plate (Oregon) beneath the North American plate. Since the deposition of the Nomlaki Tuff member of the Tehama Formation (3.4 million years ago), volcanic activity has occurred intermittently along the southern Cascade Range.

The Coast Ranges province consists of a mixture of rock types and structures ranging in age from Jurassic to Tertiary. Together, the varied assemblage of graywacke, metagraywacke, shale, chert, limestone, mafic and ultramafic rocks make up the Franciscan complex. Pervasively deformed by folds and faults, the Franciscan complex is commonly characterized by zones of extensive shearing and the presence of ophiolite-serpentinite melanges.

The Great Valley province is a 400-mile-long by 30-to 60-mile-wide sedimentary basin. At the base of the Great Valley is a fragmental assemblage of ultramafic rocks called the Coast Range ophiolite, consisting of middle to late Jurassic oceanic crust and upper mantle. One of the more complete ophiolite sequences occurs west of Red Bluff along South Fork Elder Creek (Sucheck, 1984). North from Elder Creek, the Coast Range ophiolite narrows and then terminates. Above the ophiolite are late Jurassic to late Cretaceous marine sandstone, shale and conglomerate of the Elder Creek terrane and the Great Valley Sequence. These were deposited in the western continental forearc basin during the middle to late Mesozoic.

The Elder Creek terrane is comprised mostly of mudstone, with minor sandstone and conglomerate. The ophiolite is considered to be part of this terrane. The Great Valley Sequence unconformably overlies the Elder Creek terrane. The Sequence crops out in a wide belt along the valley's western foothills. The Sequence consists of interbedded middle to late Cretaceous sandstone, conglomerate and mudstone. The bedding dips east and strikes northwest, forming long linear ridges and valleys.

## **Geologic Units in the Study Reach**

Younger deposits consist of sedimentary and volcanic deposits of Tertiary and Quaternary age, such as the Tehama Formation, the Nomlaki Tuff member and the Red Bluff Formation. Quaternary alluvium, basin, marsh and terrace deposits cap the sequence. The study reach is underlain by these younger units. The distribution of geologic units are shown on Plates 1, 2, and 3.

### **Tehama and Tuscan Formations**

The Pliocene Tehama Formation underlies much of the valley and lower foothills region on the west side. The clast lithologies indicate that these Tertiary semiconsolidated fluvial deposits were derived from the Coast Ranges and Klamath Mountains to the west and northwest (Russell, 1931). The Tuscan Formation is similar in depositional mode and form but is derived from the volcanic Cascade Range on the east side.

It is exposed along near vertical Sacramento River banks in a number of places such as Red Bluff, Woodson Bridge and Hamilton City. The Tehama Formation is composed of fluvial sedimentary deposits of semi-consolidated pale-green, gray and tan sand, tuffaceous sand, silt, and clay. The Formation has scattered, discontinuous lenses of gravel. The Tehama grades finer away from the source areas. The Formation has a low regional dip towards the east and the



Sacramento River. The Nomlaki Tuff member is a Pliocene, white to light-gray dacite pumice tuff and lapilli tuff that occurs near the base of the Tehama Formation. The bedding probably conforms with the shallow eastward dip of the Tehama Formation. The member is a massive, non-layered volcanic ash that forms resistant vertical banks along tributary streams and gullies. Maximum thickness is approximately 30 feet.

In general, the Tehama Formation forms rounded hills with moderate relief and has a thin soil cover. Along tributary streams, exposures form 20-to 60-foot high vertical bluffs. Cut-banks with 1:1 and steeper slopes are normally stable.

Exposures of the Tertiary Tuscan Formation in the valley typically consist of volcanic-derived siltstone, sandstone and conglomerate. The Tuscan is exposed in the stream channels of eastside tributaries in areas too small to show on the geologic map. In other areas, it is typically overlain by more recent deposits.

### Red Bluff Formation

The Pleistocene Red Bluff Formation is a coarse gravel deposit with a brick-red clayey matrix. This Formation originally formed on a regional, gently inclined erosional surface, or pediment, on the Tehama Formation. Erosional remnants of the Red Bluff crop out as far north as Lake Shasta, along the western base of the Coast Ranges, along ridges between watersheds and on both sides of the valley floor as far south as Princeton. The Red Bluff is fairly thin, ranging from 6 to 15 feet thick.

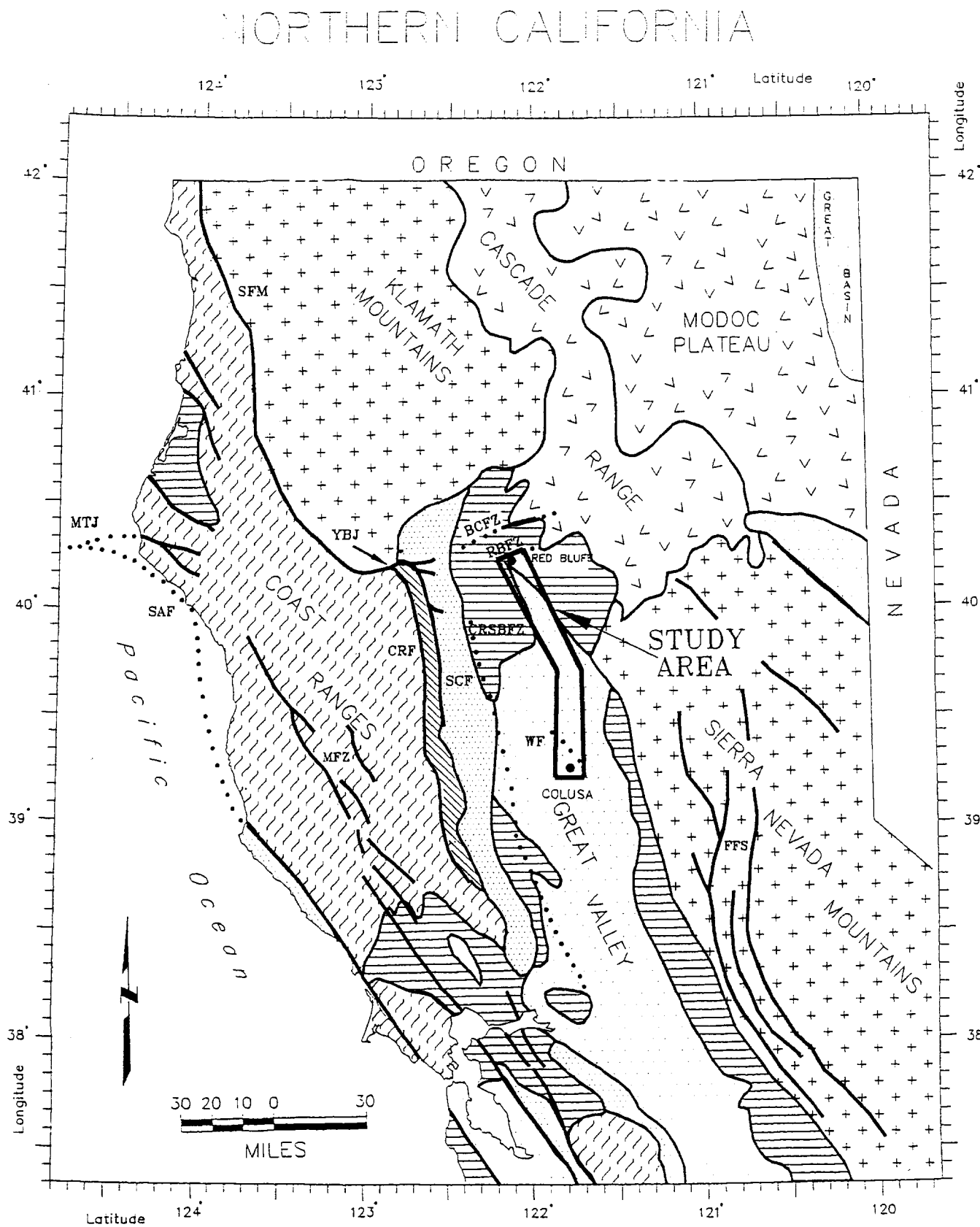
### Terrace Deposits

The Sacramento River and major tributaries have developed a set of flanking terrace levels. These terraces stair-step in elevation away from the active channel, with the upper terraces the oldest. A typical terrace consists of several to 10 feet deep dark gray, fine sand and silt overlying four to six feet of poorly sorted cobbly gravel. The older terrace deposits are typically more elevated and have more developed soils.

Terrace deposits are typically complexly intertwined, and each terrace may have several minor deposits of different age and elevation associated with it. These are typically not differentiated. Seven to nine terrace levels have been identified along tributaries. Four of these have been given formational names and occur near the Sacramento River.

These four Pleistocene terraces are the Upper Riverbank, Lower Riverbank, Upper Modesto and Lower Modesto. These terraces have been correlated by their absolute age, soil stratigraphy, geomorphic expression to the Riverbank and Modesto Formations of the San Joaquin Valley (USGS, 1984).

Riverbank Formation. The Pleistocene Riverbank Formation has been divided into an upper and lower member. These are combined into one unit on the geologic map. The lower member is



LEGEND

- FAULTS**
- Geologic Contact
  - Fault, dotted where concealed
  - SAF San Andreas Fault
  - CRF Coast Range Fault
  - SFM South Fork Mountain Fault
  - SCF Stony Creek Fault
  - BCFZ Battle Creek Fault Zone
  - MFZ Maacama Fault Zone
  - FFS Foothills Fault System
  - YBJ Yolla Bolly Junction
  - MTJ Mendocino Triple Junction
  - ECFS Elder Creek Fault Zone
  - OFF Oak Flat Fault
  - SSF Sulphur Spring Fault
  - CFFZ Cold Fork Fault Zone
  - RBFS Red Bluff Fault Zone
  - CRSBFZ Coast Range-Sierran Block Boundary Fault Zone
  - WF Willows Fault
- GEOLOGIC UNITS**
- Quaternary Sedimentary Deposits
  - Quaternary and Tertiary Volcanic Rocks of the Cascade Range and Modoc Plateau.
  - Tertiary Sedimentary Deposits
  - Upper Jurassic/Cretaceous sedimentary rocks of the Great Valley
  - Upper Jurassic/Cretaceous Sedimentary Rocks of the Coast Ranges
  - Upper Jurassic to Cretaceous Mafic to Ultramafic rocks
  - Mesozoic - Paleozoic Metamorphic and Granitic Rocks of the Klamath and Sierra Nevada Mountains.

STATE OF CALIFORNIA  
THE RESOURCES AGENCY  
DEPARTMENT OF WATER RESOURCES  
NORTHERN DISTRICT

Sacramento River  
Bank Erosion Investigation

Regional Geologic Map

lithologically similar to the Red Bluff Formation and has nearly the same red color, and consists of gravel, sand, silt and clay. It occurs on the higher of two flat terraces that have been cut and filled into the surface of the Red Bluff or Tehama Formations.

The upper member is younger, and formed during a long period of stable climatic conditions. This member occurs as extensive flat stream terraces along the major creeks.

A typical outcrop consists of 8-10 feet of tan to light brown sandy silt underlain by 1-3 feet of gravel and a few rocks up to eight inches in diameter. Soils of the member display medial development with strong textures. The soil contains a B-horizon and local hardpan but profile development is not as great as on the lower member.

Modesto Formation. The Modesto Formation has also been divided into an upper and lower member that were combined on the geologic map. The lower member is the youngest terrace that has a pedogenic B-horizon. Terraces display fresh depositional morphology with few erosional features. The Upper Modesto does not have a soil horizon. This unit borders existing channels and is generally less than 10 feet thick. It is composed of gravel, sand, silt, and clay.

### Paleochannel Deposits

Paleochannels were identified (Robertson, 1987) along the eastern margin of the Sacramento River from the latitude of Thomas Creek to near the town of Colusa. These braided paleochannels, with multiple branches and islands, are a striking departure from the meandering channel of today. The braided morphology of these channels suggest a higher bedload, a higher width to depth ratio, and higher discharges than the present Sacramento River. The age of these channels is believed to be between 150,000 and 450,000 years based on buried soils (Robertson, 1987). This is equivalent to the Riverbank Formation in age. In most areas the paleochannels have a thin cover of silt and clay mapped in various areas as lower Modesto or basin deposits (Helley and Harwood, 1985). The paleochannel deposits are mapped as older channel deposits on the geologic map.

The bedload was considerably coarser than that in the present Sacramento River and consisted mostly of volcanic rocks, suggesting a Cascade Range source area. The deposit may date back to a period of high volcanic activity near the Lassen area. These deposits are fairly well indurated and erosion resistant. The western edge of the paleochannel is the eastern edge of the historic meander belt.

### Alluvial Fan Deposits

Alluvial fans occur near the edge of the valley on some of the tributaries. Most notable are the Antelope, Mill, Deer, Big Chico and Stony Creek fans. Most of these fans have several or more abandoned channels visible on aerial photographs and topographic maps. Fan deposits on the east side tend to be well indurated, with cobbles and boulders in a matrix of gravel, sand, silt and clay. A considerable amount of volcanic ash is evident in the matrix.

Westside fans tend to be gravelly. The Stony Creek fan is the largest and has numerous abandoned channels, some of which flowed south into the Colusa Basin.

### Historic Meander Belt

This belt is older than the 100-year meander belt and is delineated using aerial photographs. Oxbow lakes, meander scrolls, sloughs and curved lines of riparian vegetation are indicators of old river channels. Agriculture, particularly through land leveling and riparian vegetation removal has erased much of the evidence. Delineation of this belt is also dependent on the time necessary for river processes to remove evidence naturally.

Two features are differentiated. These are oxbow lakes and meander point bar scrolls. Oxbow lakes are remnant river channels separated from the active channel by meander avulsion. Point bar scrolls are distinctive curvilinear depositional features left by the river as it meanders across the flood plain. The more distinct scrolls are shown as dashed lines on the geologic map.

The historic meander belt includes an unspecified amount of time, probably in the range of 100-to-1000 years.

### 100-Year Meander Belt

This belt is smaller than the historic meander belt. The belt is delineated using old survey maps, topographic maps and photographs showing actual river channels at specified times. This belt was mapped by DWR (1984) and shown on the "*Middle Sacramento River Spawning Gravel Study: River Atlas*." It was updated using 1991 aerial photographs and plotted at a scale of 1 inch equals 4,000 feet.

### Undifferentiated Stream Alluvium

This unit is deposited by the river but does not show the distinctive fluvial geomorphic features of the 100-year or historic meander belts, either because of changes with time or extensive agricultural development.

### Basin Deposits

Basin deposits are fine-grained silt and clay derived from the Sacramento River and tributaries that deposited in local basins, the Butte Basin on the east or the Colusa Basin on the west. The clay-rich deposits are especially suitable for rice production. Thickness varies from several to almost 200 feet.

### Marsh Deposits

Marsh deposits are fine-grained, very organic rich sand, silt and clay associated with the basin deposits. They are differentiated from the basin deposits by generally being under water.

### Stream Channel Deposits

Tributary stream channel deposits occurs as loose, unconsolidated sand and gravel in the active stream channel. Sacramento River stream channel deposits occur within the 100-year Meander Belt and are not differentiated.

### Floodplain Deposits

These deposits occur as sand, silt and clay with minor lenses of gravel on the flood plain adjacent to the active channel. The floodplain deposits form an approximately flat terrain broken by oxbow lakes and meander scrolls. The floodplain receives a thin cover of sand and silt during floods, thereby replenishing that lost through bank erosion. These deposits are not differentiated on the geologic map because they are contiguous with the historic and 100-year meander belts.

## **Geologic Structure**

The main geologic structures in the study area include faults, folds, and bedding. The southeast to northwest trending isoclinal folding of the Great Valley Sequence is the most prevalent structural feature on the valley's west side. It strongly influences the regional topography, which consists of a series of northwest trending ridges and valleys. The Chico Monocline is the most significant structure on the east side. A number of fold axes and buried faults cross the Sacramento River.

### Folds

The Sacramento Valley is a northwest-trending, asymmetric synclinal trough filled with a thick accumulation of sediments in excess of 60,000 feet thick. Upper Jurassic to Cretaceous east-dipping sediments of the Great Valley Sequence are isoclinally folded along the west side of the valley.

The Chico monocline is the most distinctive feature on the east side. A series of parallel folds and associated tension faults trend north-norwest through the west-dipping monoclinally folded beds of the Tuscan Formation. The age is believed to be between 2.4 and 1.1 million years (Harwood and Helley, 1982).

The Inks Creek fold system crosses the Sacramento River a few miles north of the study reach. Here the Sacramento River is obviously structurally controlled. It flows southwest around the nose of a plunging anticline near Jellys Ferry, northwest around a syncline at Table Mountain and around another fold at Bend, before entering the Sacramento Valley proper at Red Bluff.

The Tehama Formation unconformably overlies the Great Valley Sequence. The Tehama dips slightly eastward. The surface of the Red Bluff Formation also appears to have been somewhat

folded, particularly toward the center of the valley. This is shown on a structural contour map by Harwood and Helley (1982) and indicates that Quaternary to Recent structural deformation is ongoing in the Sacramento Valley.

Near Corning the Red Bluff Formation is folded to form the Corning domes. The age of this period of deformation is estimated to be between 1.1 and 0.45 million years (Harwood and Helley, 1982).

Harwood and Helley (1987) identified two minor folds that parallel the course of the Sacramento River. These are the Los Molinos syncline, located between Red Bluff and Los Molinos, and the Glenn syncline, located between Woodson Bridge and Glenn. These narrow synclines coupled with the Corning domes to the west and the Chico monocline to the east have tightly controlled the course of the Sacramento River and influenced alluvial deposition during the late Quaternary. South of this area, late Quaternary alluvial deposits spread laterally across much of the valley and over the Glenn syncline, the actual trace of which controls the present course of the river as far south as the town of Glenn.

### Faults

The Stony Creek and Coast Range faults extend southward through the Red Bank, Elder and Thomes creek watersheds on the Sacramento Valley westside. The Elder Creek fault, believed to be late Cretaceous (ESA, 1980), is found in the upper reaches of Elder Creek. The Coast Ranges-Sierran Block Boundary has also been postulated to be an active tectonic zone that lies hidden beneath the entire length of the western Sacramento Valley (Wong, et al. 1988).

The Battle Creek fault system includes a series of northeast trending faults and the associated Inks Creek fold belt that crosses the valley north of Red Bluff. Tuscan and Tehama Formation beds have been uplifted from 150 feet on the west to 1,450 feet on the east. The age is estimated at about 0.45 million years.

The Red Bluff fault is a subsurface feature that extends northeast and southwest from Red Bluff. The location is shown on a map from Harwood and Helley (1987) and is based upon proprietary subsurface data. They report that there are no surface features that can be associated unequivocally with the fault even though there may be as much as 450 feet of subsurface vertical offset, south side down.

The Willows fault is a major northwest-trending subsurface fault that crosses the Sacramento River north of Colusa, follows the river for 15 miles, diverges from the river below Princeton and leaves the river corridor near Butte City. Uplift is on the east side of this fault. It intersects the Corning Fault, which trends northward to Red Bluff. Field investigations and subsurface data indicates that the youngest deposits deformed by the Corning fault are gravels of the Red Bluff Formation, dated at between 0.45 and 1.1 million years old.

## Tectonic setting

Plate tectonics have played a major role in the tectonic development of California. From late Jurassic to mid-Tertiary, the eastern Pacific oceanic lithosphere (Farallon plate) was subducted beneath the western margin of the North American continental plate. This subduction resulted in the formation of an arc-trench system that included an accretionary prism, a forearc basin, and a magmatic arc. Today these terranes are represented by the Franciscan complex, the Great Valley Sequence, and the Klamath and Sierran plutonic/metamorphic belt, respectively. Figure 4 is a pictorial cross-section from west to east across Northern California showing these features.

Throughout Cretaceous time, rocks eroding from the surrounding plutonic and metamorphic belts were deposited by submarine turbidity currents into the deep forearc basin. These sediments, the Great Valley Sequence, continued to accumulate, filling the forearc basin to near sea level by Paleogene time. During this same period, ocean floor and trench deposits of the Franciscan complex were being dragged down by the Pacific plate, and underthrust in a wedge against the continental margin and beneath the Great Valley sediments (Ingersoll, 1983). Subsequent underthrusting resulted in the sediments of the forearc basin to be uplifted and tilted to the south and east (Harwood and Helley, 1987).

Marine deposition and subduction continued through Oligocene time. As subduction ceased during mid-Tertiary, uplift became more rapid and the transition to a strike-slip regime began offshore in southern California. This transition led to the formation of the San Andreas fault.

As the San Andreas fault evolved, a triple junction between the Pacific-Farallon, North American, and Gorda lithospheric plates began to develop and migrate slowly northward. During this period, the Great Valley experienced several episodes of uplift and subsidence. By early Miocene, most of the northern valley had emerged from the inland seas and was subjected to fluvial erosion and deposition (Harwood and Helley, 1987). Concurrently, volcanic eruptions were occurring along the northern Sierra Nevada, damming streams and filling narrow valleys. At about the same time, extensional forces from behind-the-arc spreading east of the Sierra Nevada reached their peak. These forces are responsible for the rapid uplift of the Sierra Nevada.

By early Pliocene, the Mendocino Triple junction had migrated north to the same latitude as the study area. Evidence suggests that as the triple junction continued to move northward offshore, structures in the valley began to simultaneously exhibit compressive deformation along a similar northward-progressive pattern (Harwood and Helley, 1987).

By the Pliocene, the Great Valley Sequence had been regionally tilted and had gone through several cycles of uplift and erosion. During the Pliocene, continental sediments of the Tehama and Tuscan Formations were deposited as large coalescing alluvial fans over the sedimentary rocks at the foot of the emerging Coast Ranges and Cascade Range. The Nomlaki Tuff Member, which occurs locally at or near the base of both formations, is an ash fall from volcanic eruptions that blanketed much of the northern valley about 3.4 m.y. ago.

Eventually, the Tehama and Tuscan Formations covered the Great Valley Sequence with sediments to a depth of 0-2,500 feet on the eroded surface of the tilted sequence (Earth Sciences Associates, 1980). Subsequent erosion and redeposition have formed the present outcrop patterns of geologic units. Fluvial processes have formed the terrace and alluvial deposits as they appear today.

Presently, the Gorda plate is subducting beneath the North American plate. Activity associated with this movement includes the surface folding, faulting and uplift of the northern Coast Ranges, and in a 152-mile long zone of eastward dipping intermediate-focus earthquakes. Beneath the basin, several intermediate and deep-focus Magnitude 4 earthquakes correlate with the Gorda plate subduction (Cockerham, 1984; Walter, 1986).

Presently, the northern Sacramento Valley lies between the large-scale right-lateral transform tectonism of the San Andreas fault to the west, and the major east-west crustal extension of

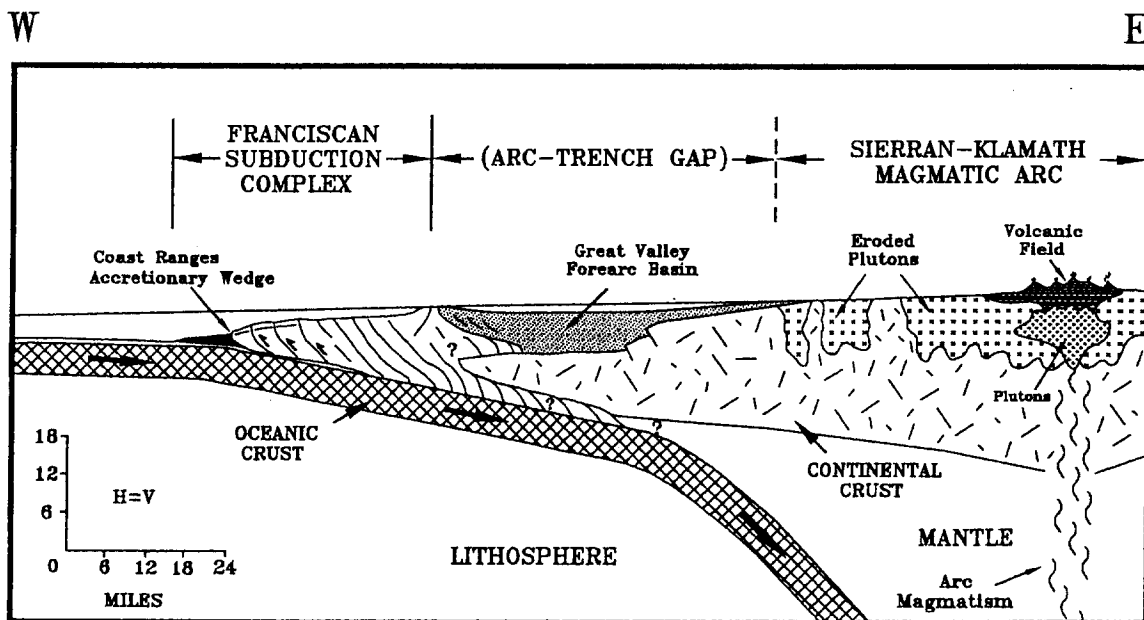


Figure 4 Schematic Profile of Subduction System Across Northern California During the Late Mesozoic.



the northern Basin and Range province to the east. The direction of stress may vary locally, but in general, the direction of maximum compressive stress is approximately northeast-southwest.

Evidence of this stress regime manifest itself as a series of northwest trending folds and faults along the western Sacramento Valley. The faults dip steeply east, with reverse and minor left-lateral movement. In the northern valley to the north of Red Bluff, the structural trend shifts and folds and faults become oriented in a more east-to-northeasterly direction. These faults typically dip steeply to the south, with normal offset and minor right-lateral movement.

Recent studies suggest that uplift along folds paralleling the western valley is active, and may represent the shallow expression of deeper thrusting. Interpretation of seismic reflection data (Unruh, 1991) indicates that these folds are caused by active thrusting along a very large triangular wedge of rocks. This imbricate zone of detachment faults may represent the boundary between the rocks of the Coast Ranges, Great Valley, and Sierra Nevada. Additional evidence presented by Wong (1988), Stein (1989), and Wentworth and Zoback (1990), suggests that this zone of faulting (commonly referred to as the Coast Ranges-Sierran Block boundary zone) extends the full length of the western valley and is most likely responsible for the two 1892 Winters/Vacaville earthquakes (Magnitude 6-7) and the 1983 Coalinga earthquake (Magnitude 6.7).

## **Geomorphology of the Study Reach**

Below Red Bluff, bank erosion and lateral migration across the floodplain were natural processes. Large floods would uproot streamside vegetation, causing banks to recede and the river to meander. Sediment derived from tributaries and from bank erosion deposited in overbank areas where vegetation reduced water velocities.

Over a period of years, erosion and deposition were roughly in balance, so that the valley floor neither aggraded nor degraded. The riparian forests played two important roles by reducing bank erosion and by inducing deposition on the floodplain.

The geomorphic characteristics of the study reach are an intrinsic function not only of the geology underlying and surrounding the river, but also of the regional climate and river hydrology. Human induced changes, such as dams, levees and diversions have also had a profound effect.

Above the study reach, the upper Sacramento River between Red Bluff and Redding is bounded and underlain by the Tertiary-Quaternary Tehama Formation, consisting of semi-consolidated fluvial deposits, and the Tertiary Tuscan Formation, consisting of interbedded lahars, volcanic conglomerate, volcanic sandstone, siltstone and pumiceous tuff. These resistant deposits confine the river, resulting in a relatively stable river course.

Reach 6 exhibits a marked tendency for anabranching, channel meandering, and bank erosion. This meandering is constrained to a relatively narrow belt by tectonic deformation and older terrace deposits from the west and conglomerates from the east. These geologically older alluvial deposits are elevated above the present river channel and act as geologic control in such places as Tehama and Woodson Bridge. The floodplain has an average width of about 2-1/2 miles.

Reach 7 is between Chico Landing and Butte City. Here the gradient is less; the river tends to be more sinuous with fewer islands. The most distinctive feature of this reach is the gradual downstream development of natural levees. This reach has been divided into three subreaches (7A to 7C), based on the criteria used for Reach 6.

Reach 7 is similar to Reach 6 in that it has an alluvial channel and is meandering. However, it is distinguished by a lesser gradient, a decrease in variability of the river width, fewer islands, more pronounced sinuosity, and the gradual downstream development of natural levees (USGS, 1977).

Reach 8 is between Butte City and Colusa. This reach is also divided into three subreaches (8A to 8C). It differs from Reach 7 by its distinctive meander wavelength.

In Reach 8, the width and width variability of the river decreases further as the natural levees increase in height and width, and the river gradually loses any tendency toward anabranching or braiding. Abandoned cutoff loops on the floodplain are infrequent and tend to be narrow and elongated, a characteristic of a naturally leveed stream. Reach 8 is constrained on the east by the paleochannel deposits and on the west by fan deposits, terrace deposits, and in places, the Tehama Formation.

### Meandering

Meandering is defined as a characteristic habit of a mature river where it winds freely on a broad flood plain. The curves are formed by the bank erosion-point bar deposition process. Erosion is greatest across the channel from the point bar. As the point bars build out from the downstream sides of the bar, the bend gradually migrates down the valley. As the meander moves laterally and longitudinally, the loops move at unequal rates, resulting in meander cutoffs, oxbow lakes, and irregularities in the channel. On the Sacramento, however, most loops are bypassed by chute cutoffs.

Meandering rates are highly variable. A river may change little in many years, yet experience rapid movement in one flood season. Different stream reaches have widely varying meander rates depending on such factors as bed and bank composition, sediment transport, flow, bank protection, and riparian vegetation.

One of the earliest surveys was made by the U.S. Army Corps of Engineers in 1896, when detailed studies were conducted on the Feather and Sacramento Rivers. Additional Corps surveys were made in 1908, 1923, and 1935.

From the middle and late 1930s to 1991, the channel location was determined using U.S. Soil Conservation Service aerial photographs, U.S. Geological Survey topographic maps and Corps and DWR river atlases.

Meander lines between Colusa and Keswick Dam have been published in the *Middle Sacramento River Spawning Gravel Study Atlas* (DWR, 1984) and the *Upper Sacramento River Spawning Gravel Study Atlas* (DWR, 1980). These reports show meander lines up to 1981 and 1976 respectively.

Plates 4, 5, and 6 show the meander belt at a scale of 1 inch equal to 4000 feet. The meander lines represent the location of the river at various times, as delineated on aerial photographs, surveys and topographic maps. The meander lines were plotted in Autocad and have been added to the DWR Northern District's Geographic Information System.

Figure 5 shows the variation in meander belt width from Red Bluff to Colusa. The width is determined from the greatest extent of all the meander lines from 1896 to 1991, as measured perpendicular to the general trend of the meander belt. The width, and hence bank erosion, is highly variable, ranging from less than 500 feet to 7000 feet. Certain short reaches of river appear to be stable.

The Figure shows three distinct patterns. The first extends between River Mile 243 (Red Bluff Diversion Dam) and River Mile 198 (a few miles above Chico Landing). The second extends between River Miles 198 and 165 (Princeton) and the third between River Miles 165 and 143 (Colusa). There appears to be a certain periodicity in the spacing of the unstable areas. Between Red Bluff and Chico Landing, the spacing is about eight miles. Between Chico Landing and Princeton, it is about 4 miles. Between Princeton and Colusa, the spacing is about 10 miles.

### Sinuosity

Analyses of channel length and sinuosity were done on eleven sets of maps and photographs dated between 1896 and 1987. No trends were apparent, except that some reaches are increasing in length and sinuosity and others are decreasing.

The 14 geomorphic reaches in the study area from Red Bluff to Colusa were evaluated for centerline distances and sinusoidal ratios, then compared with similar historical values (see Table 2). Centerline lengths were measured from the June 1987 aerial photos. Sinuosity ratios were calculated using the ratio:

$$\text{Sinuosity Ratio} = \frac{\text{measured centerline length of reach}}{\text{down valley length of reach}}$$

River meanders were delineated by tracing the maximum left and right bank extent of the current river channel.

### Centerline Length

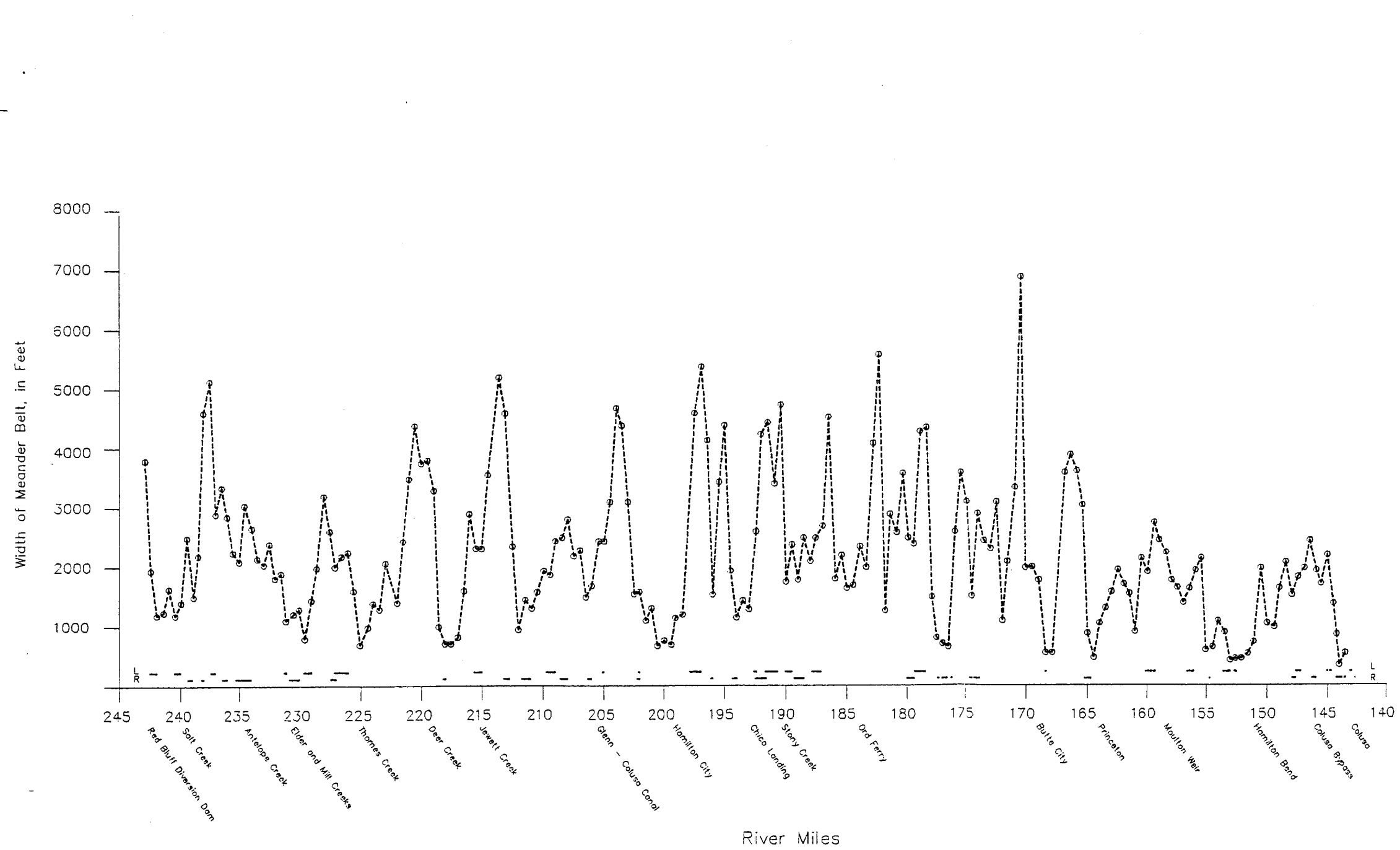
Centerline lengths of the Sacramento River were measured on maps and aerial photos ranging from 1896 to 1987. Table 3 shows the centerline lengths by reaches.

### Bank Protection

In Reach 6, approximately between Red Bluff and Chico Landing, 103,500 feet of riverbank have been riprapped and an additional 81,000 feet of riprap have been proposed. If this is developed, the total riprap in this reach would comprise 35 percent of the riverbank. In Reach 7, River Mile 193 to 165, 48,000 feet or 16 percent of the banks are protected and an additional 10 percent are planned (USCE, 1988). Reach 8 has 26,400 feet of bank protection, or about 12 percent of the banks. Table 4 shows Federal and private bank protection projects between Colusa and Red Bluff.

Bank protection, when effective, stops bank erosion and lateral migration. It prevents loss of valuable agricultural lands, transportation facilities, and structures.

Bank protection, particularly if it is along all the eroding banks of the river, will cause some long-range geomorphic changes. First, it will have a stabilizing effect on length and sinuosity. Second, it will prevent the re-entrainment through bank erosion of gravel deposited on point bars. This will have some long-range effects on the amount of available spawning gravel. Third, over a period of time, it will tend to narrow the channel, increase the depth of flow, and reduce the hydrologic diversity. Sloughs, tributary channels, and oxbow lakes will fill with sediment over time and no new ones will be created. This will result in loss of valuable wetland habitat along the river corridor.



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Sacramento River  
Bank Erosion Investigation

Variation in Meander Belt Width  
Red Bluff to Colusa

**TABLE 2 CENTERLINE SINUOSITY  
SACRAMENTO RIVER FROM RED BLUFF TO COLUSA**

Date of Survey											
Reach	1896	1908	1923	1937	1946	1956	1960	1964	1969	1981	1991
6A	1.15	1.15	1.15	1.15	1.50	1.50	1.50	1.50	1.28	1.28	1.10
6B	1.20	1.20	1.33	1.33	1.18	1.15	1.15	1.15	1.40	1.40	1.20
6C	1.16	1.16	1.16	1.16	1.15	1.10	1.10	1.10	1.17	1.17	1.04
6D	1.28	1.27	1.32	1.32	1.25	1.24	1.24	1.24	1.35	1.37	1.42
6E	1.24	1.24	1.26	1.26	1.28	1.32	1.32	1.32	1.32	1.33	1.08
6F	1.41	1.41	1.35	1.35	1.41	1.36	1.36	1.36	1.57	1.26	1.28
6G	1.27	1.27	1.27	1.27	1.30	1.44	1.44	1.44	1.34	1.37	1.00
6H	1.71	1.71	1.90	1.90	1.22	1.27	1.21	1.21	1.31	1.10	1.30
7A	1.61	1.48	1.48	1.51	1.49	1.37	1.37	1.50	1.57	1.73	1.73
7B	1.14	1.14	1.14	1.18	1.11	1.11	1.11	1.07	1.08	1.08	1.00
7C	1.43	1.15	1.15	1.40	1.05	1.05	1.05	1.13		1.28	1.34
8A	1.33	1.41	1.41	1.27	1.13	1.13	1.16	1.16	1.16	1.21	1.30
8B	1.17	1.17	1.17	1.20	1.20	1.20	1.20	1.21	1.21	1.21	1.27
8C	1.86	1.71	1.71	1.52	1.76	1.76	1.76	1.69	1.69	1.64	1.85

**TABLE 3 CENTERLINE LENGTH OF THE SACRAMENTO RIVER  
RED BLUFF TO COLUSA (1896-1991) IN FEET**

Reach	1896	1908	1923	1935	1937	1946	1955	1960	1964	1969	1981	1991
6A	17,500	17,500	17,600	17,600	17,600	22,400	22,900	22,900	22,900	19,500	19,500	22,700
6B	33,500	33,500	37,300	37,300	37,300	33,000	32,100	32,100	32,100	39,000	39,000	35,600
6C	13,300	13,300	13,300	13,300	13,300	13,200	12,600	12,600	12,600	13,400	13,500	12,500
6D	48,800	48,300	50,300	50,300	50,300	47,500	47,100	47,100	47,100	57,400	52,100	51,400
6E	11,800	11,800	12,000	12,000	12,000	12,000	12,500	12,500	12,500	12,500	12,600	13,600
6F	68,400	68,400	65,400	65,400	65,400	68,400	66,000	66,000	66,000	76,000	61,000	61,900
6G	17,200	17,200	17,200	17,200	17,200	17,600	19,500	19,500	19,500	18,100	18,500	13,000
6H	30,000	30,000	33,000	33,000	33,000	21,400	21,200	21,200	21,200	22,900	19,300	24,900
7A	86,800	79,400	79,400	74,200	81,200	79,900	73,700	73,700	80,400	84,600	83,200	90,600
7B	10,500	10,600	10,600	10,500	10,900	10,300	10,300	10,300	9,000	10,000	10,000	8,600
7C	57,200	48,000	46,000	49,000	56,500	48,200	47,000	47,000	51,500	51,500	51,800	57,000
8A	60,500	58,400	58,400	53,200	55,000	49,000	52,000	52,000	50,500	50,500	52,200	51,200
8B	20,500	21,500	21,500	22,100	22,800	21,900	21,800	21,800	22,400	22,400	22,500	18,200
8C	31,600	32,900	32,900	33,400	33,000	32,400	33,000	33,000	28,200	28,200	29,200	35,400

**TABLE 4 BANK PROTECTION PROJECTS  
COLUSA TO RED BLUFF**

River Mile	Bank	Length (feet)	Year Constructed
143.5	right	450	*
143.8	right	2900	*
144.7	left	1930	*
145.0	left	730	*
146.0	right	2150	*
147.3	left	830	*
147.6	left	1100	*
147.7	right	1930	*
148.0	right	450	*
152.5	left	710	*
152.6	left	300	*
153.0	left	3300	*
154.7	right	600	*
156.1	left	3170	*
159.3	left	900	*
159.6	left	1200	*
159.8	left	2000	*
164.7	right	1700	*
165.1	right	1050	*
168.4	left	750	*
173.8	right	450	*
174.0	right	1360	*
174.4	right	1565	*
176.2	right	440	*
176.6	right	2500	*



**TABLE 4 BANK PROTECTION PROJECTS  
COLUSA TO RED BLUFF (Continued)**

River Mile	Bank	Length (feet)	Year Constructed
176.8	right	475	*
177.3	right	650	*
177.4	right	470	*
178.5	left	4900	*
179.4	right	2460	*
179.5	right	2972	*
187.1	left	645	*
187.1	left	2805	*
187.2	left	670	*
187.4	left	2600	*
188.5	right	4600	*
188.8	right	1800	*
189.5	left	3000	*
190.7	left	5537	*
191.6	right	5100	*
192.4	left	1200	*
194.0	left	2800	1973
196.3	left	2100	1973
197.0	right	6400	1975
199.5	left	4000	(private)
202.0	right	600	1975
204.4	left	1300	1976
204.9	right	1240	1978
206.5	right	700	(private)
207.0	right	1900	1976
208.4	left	4470	1974

**TABLE 4 BANK PROTECTION PROJECTS  
COLUSA TO RED BLUFF (Continued)**

River Mile	Bank	Length (feet)	Year Constructed
209.0	right	4000	1983
211.1	left	4000	1976
213.1	left	2080	1974
215.0	right	2300	1982
216.5	left	11000	(private)
218.3	left	587	1970
219.4	left	2580	1963
220.3	right	4800	1963
226.3	right	7300	1978
227.0	right	6500	1983
227	left	1300	(private)
229.0	right	3200	1975
229.2	right	500	1968
230.5	left	3500	1975
231.2	right	1000	1978
233.9	left	1400	1978
234.2	left	2040	1963
234.7	left	2140	1963
235.8	left	2600	1971
237.2	right	3700	1963
239.1	left	2650	1963
240.0	left	2700	1963
241	right	3500	1983
242.6	left	2600	1978

\* Date not available



## **HYDROLOGY**

The study reach lies in the Sacramento Valley between the Red Bluff Diversion Dam and Colusa, a river distance of about 96 miles. The contributing drainage area between the Sacramento River above Bend Bridge gaging station and the Sacramento River at Colusa gaging station comprises 3,190 square miles.

Within the study area are a number of tributary streams, some of which are gaged. Gaged tributaries entering from the west side include Red Bank, Elder, and Thomes Creeks. Entering from the east side are Antelope, Mill, and Deer Creeks.

Precipitation in the study area is seasonal, with more than 80 percent in December, January, and February. Precipitation varies with elevation and from west to east because of the rain shadow effect on the east slope of the coast range. The average annual rainfall is 22 inches in the valley and flanking hills, increasing to 70 inches in the headwaters of Thomes Creek, and to 90 inches in the upper Mill Creek drainage.

The drainage above Red Bluff, including the Pit and McCloud Rivers and headwaters of the Sacramento River, comprises an area of 8,900 square miles. The northernmost area lies in the high, wet regions of the Cascades and the Klamath Mountains. The runoff from this area reflects the precipitation pattern -- high flows occur from direct precipitation between November and April; April and May are months of large sustained flows from snowmelt. Low flows occur during July, August, September, and October. Prior to dams and diversions, the combined flows from the Cascade and Klamath Mountains during winter and spring months caused severe flooding and damage in the Redding basin and Sacramento Valley, while hot, dry summer months provided little water to irrigable lands.

Hydrologic changes in the watershed that affect conditions in the study reach are caused mostly by dams and diversions. These include changes in mean monthly discharge, peak monthly discharge, flow duration, flood peaks, and flood frequency.

### **Dams and Diversions**

Numerous small dams and diversion structures were built in the watershed above Red Bluff and the study area, but until the completion of Shasta Dam in 1943, they had little effect on the hydrology. Today, Shasta Dam, Keswick Dam, Red Bluff Diversion Dam, and the Trinity Project control, divert, and regulate flows in the Upper and Middle Sacramento River.

### Shasta Dam

Shasta Dam stores 4.5 million acre-feet and regulates flows of the Pit, McCloud, and upper Sacramento Rivers. The project, which began water storage and regulation in December 1943, was built for a number of uses: river flow regulation, flood control, irrigation, domestic water supply, power generation, recreation, and salinity control in the Sacramento- San Joaquin Delta.

The maximum allowable discharge from Keswick Dam is coordinated with downstream tributaries so as not to exceed 79,000 cubic feet per second at Redding, 100,000 cfs at Red Bluff, or 130,000 cfs at Hamilton City during high water periods. An attempt is made to attain a mean flow of 12,000 cfs during summer months and 6,000 cfs during winter months.

Keswick Dam, 9 miles downstream from Shasta, has a storage capacity of 23,800 acre-feet. Besides water regulation and power generation, Keswick Dam acts as a fish trapping facility. Salmon and steelhead are trapped at the dam and transported to a fish hatchery on Battle Creek.

Flow regulations at Shasta and Keswick have noticeably lowered discharge maximum and increased discharge minimums along the Sacramento River. Although mean yearly discharge was not appreciably altered, changes in seasonal discharges are considerable.

A formal agreement exists between DFG and the U. S. Bureau of Reclamation concerning minimum releases during critical spawning times. This agreement states minimum releases shall not be lower than 2,300 cfs from March 1 to August 31, 2,600 cfs from December 1 to February 28, 3,900 cfs from September 1 to November 30, except in emergency situations. Flow commonly exceeds these minimums due to power and irrigation requirements. There is no formal agreement to date concerning maximum releases during the fall spawning season.

### Trinity River Diversion

Since December 1963, water has been diverted from the Trinity River basin through the Clear Creek tunnel and Judge Francis Carr Powerhouse to Whiskeytown Lake. The Spring Creek tunnel then diverts Trinity water and most of Clear Creek water through another power plant into Keswick Lake. From 1963 to 1991, an average of a million acre-feet of Trinity River water has thus been diverted into the Sacramento River basin each year. The average between 1981 and 1991 is 905,000 acre-feet although only about 700,000 have been diverted in the last 3 years.

Since 1981, 68 percent of the releases from Clair Engle Lake (Trinity Reservoir) are diverted into the Sacramento River system. This affects the flows of both the Sacramento and Trinity Rivers. The Trinity River near Burnt Ranch has had about a 40 percent decrease, and the Sacramento River above Bend Bridge a 15 percent increase in mean annual discharge.

### Diversions Between Keswick Dam and Red Bluff

One of the first water development efforts in the Redding area resulted in the formation of the Anderson-Cottonwood Irrigation District. The District contains 33,100 acres with over 17,000 acres irrigated. The ACID Diversion Dam, the first on the Upper Sacramento River, was completed in 1918. The dam is 440 feet long, about 15 feet high, and its sole purpose is to divert water into an irrigation system.

In June 1967, the District contracted with the U. S. Government for a water supplement to their natural flow rights of 165,000 acre-feet. This contract allows for an additional diversion of 10,000 acre-feet, making a total of 175,000 acre-feet of water available to the District each year.

Water use by ACID between the months of April and October comprises about 80 to 85 percent of the approximate 190,000 acre-feet diverted yearly between Redding and Red Bluff. The remaining percentage is diverted by the City of Redding, industry, private farms, and small towns.

Many tributary streams in the study area have intricate systems of canals and dams for power generation or diversions for irrigation. Power diversions often leave long stretches of creeks dry, or at very low flows. Irrigation diversions create more drastic changes as water removed for irrigation is consumed and generally not returned to the stream.

### Diversions Between Red Bluff and Colusa

At the upper end of the study reach, the Red Bluff Diversion Dam diverts water from the Sacramento River to the Tehama-Colusa and Corning Canals. During an average water year 700,000 acre-feet are diverted to the Tehama-Colusa Canal and an additional 50,000 acre-feet are diverted to the Corning Canal.

The Glenn-Colusa Irrigation District diverts water into its main canal about 11.5 miles upriver from Chico Landing. The earliest diversion into the GCID was in 1905 when the flow capacity was 700 cfs. In the ensuing years improvements have increased canal capacity to about 3,000 cfs. The GCID now diverts an annual average of 767,300 acre-feet from the Sacramento River. Numerous smaller diversions are in the study reach.

By 1960, the average yearly diversions from the Sacramento River were about 40 percent greater than the pre-Shasta period, when diversions depended on natural runoff.

## Streamflow

Hydrologic data were developed from DWR project and water supply data, U.S. Geological Survey (USGS) gaging stations, and U.S. Army Corps of Engineers (USCE) and U.S. Bureau of Reclamation (USBR) hydrologic and dam operations data. Some of the USGS gaging stations were abandoned in 1980 and subsequently operated by DWR. The DWR data on these stations were not used or discussed because of incompatible computer data files. Figure 6 shows stream gaging station locations and Table 5 vital statistics of Sacramento River gaging stations.

Yearly changes in hydrology were determined by comparing streamflow data for the period of record. The streamflow data may conveniently be divided into the following three hydrologic periods based on major human alterations of the river regime: (1) pre-Shasta Dam (to December 1943); (2) post Shasta, but pre-Trinity River diversion (December 1943 to December 1963); and (3) post Trinity River diversion (December 1963 to present). The Trinity River diversion is also referred to as post Shasta and pre-Whiskeytown Dam.

Hydrologic changes were analyzed for the Middle Sacramento River above Bend Bridge near Red Bluff (USGS 11377100), at Vina Bridge (USGS 11383730, DWR A02700), near Hamilton City (USGS 11383800), at Butte City (USGS 11389000), and at Colusa (USGS 11389500). Streamflow was not analysed at the Ord Ferry gaging station.

The Red Bluff gage, (at Jellys Ferry, 1892-1902; near Red Bluff 1902-1967; above Bend Bridge, 1967- present) about 17 miles upstream from the Red Bluff diversion dam, has a natural watershed of 8,900 square miles. Before the Trinity diversion, average annual discharge for the period of record was 11,400 cubic feet per second. The average post Whiskeytown Dam discharge at this station is 13,360 cfs. Approximately 190,000 acre-feet are diverted between Keswick and Bend.

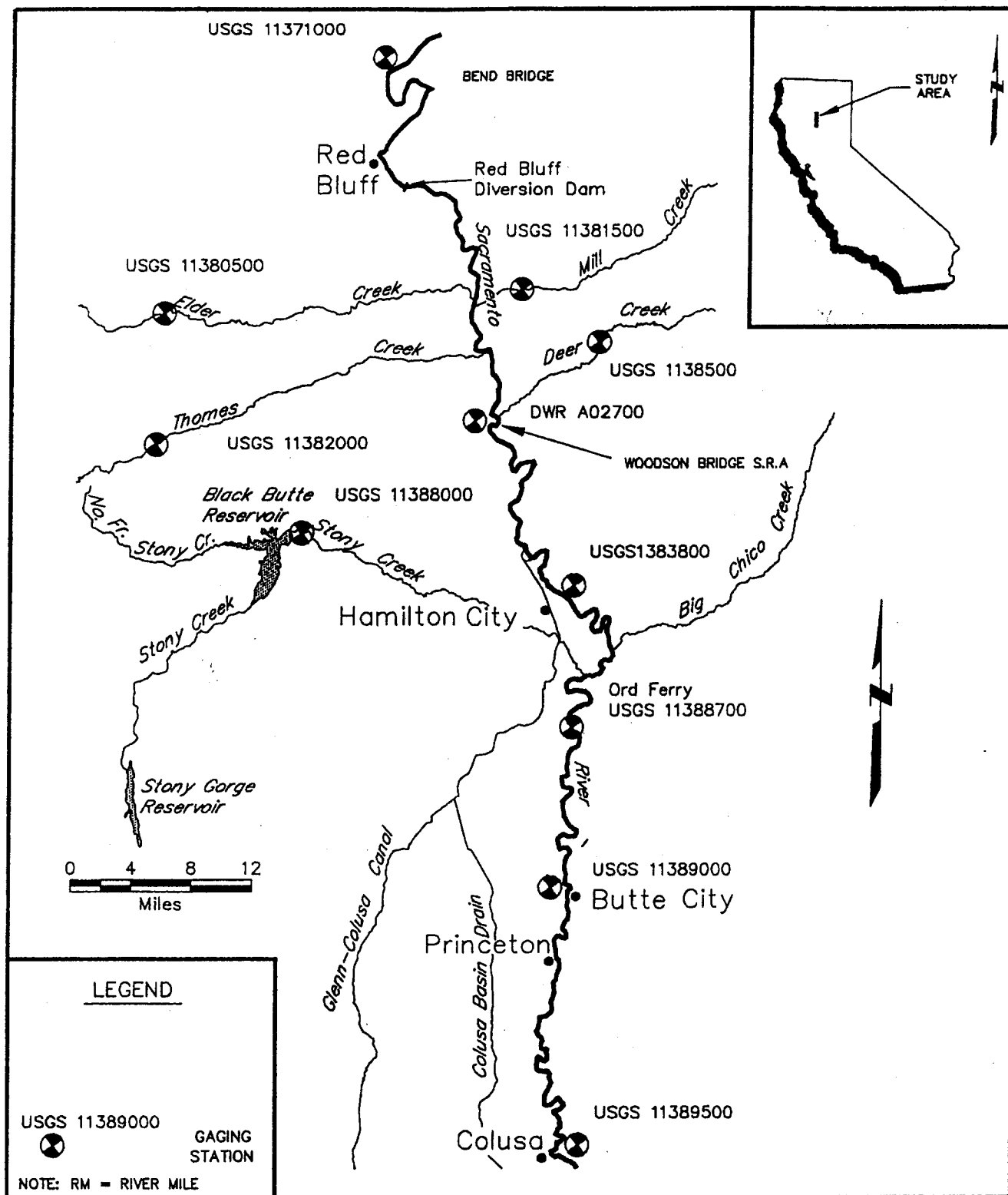
The Vina gage, about midway in the study reach, has a watershed of 10,930 square miles. The average post Whiskeytown Dam annual discharge at this station is 13,590 cfs. Approximately 950,000 acre-feet are diverted between Keswick and Vina.

The Hamilton City gage, about 4.5 miles upriver from Chico Landing, has a watershed of 11,060 square miles. The average post Whiskeytown Dam annual discharge is 13,550 cfs. An additional 760,000 acre-feet is diverted from the river between Vina and Hamilton City, for a total of 1.71 million acre-feet between Keswick and Hamilton City.

The Butte City gage is directly south of Butte City. It has a watershed area of 12,075 square miles. The average annual post Whiskeytown Dam discharge is 14,040 cfs.

The Colusa gage is at the town of Colusa. It has a watershed area of 12,090 square miles. The average annual post Whiskeytown Dam discharge is 12,130 cfs. This is less than the Vina, Hamilton City, and Butte City gages because of overflow during floods into flood control weirs.

Figure 6



# Sacramento River Bank Erosion Investigation Stream Gaging Stations Sacramento River from Red Bluff to Colusa



**TABLE 5 SACRAMENTO RIVER GAGING STATIONS**

Stream Gaging Station	River Mile	Period of Record	Drainage Area (Mi <sup>2</sup> )	Mean Annual Flow (cfs)
Sacramento River at above Bend Bridge (USGS 11371000)	260.5	1892 to current year	8,900	11,830
Sacramento River at Vina Bridge (DWR A02700)	218.3	1945 to current year	10,930	13,770
Sacramento River at Hamilton City (USGS 11383800)	199.3	1945 to current year	11,060	12,460
Sacramento River at Butte City (USGS 11389000)	169.0	1965 to current year	12,075	13,130
Sacramento River at Colusa (USGS 11389500)	143.0	1921 to current year	12,090	11,380

DWR maintains a gage at Ord Ferry not used in this analysis.

It is important to note that for the Vina, Hamilton City, Butte City and Colusa gages, overbank flow is either not gaged or not precisely gaged. Also note that the Butte City and Colusa gages have major overflow weirs such as the Moulton and Colusa weirs that divert major floodflows out of the main channel.

### Mean Monthly Flow

Figure 7 shows the average mean monthly discharge for the three hydrologic periods at the "Above Bend Bridge" gaging station. At this gage, the effect of Shasta was to reduce mean winter discharge to 80 percent of the pre-Shasta flows. However, since the Trinity diversion, the average December discharge has increased to 130 percent of the pre- Shasta normal, January flows are near normal, and February flows are about 75 percent of normal. The most striking changes, however, have been in summer and fall flows. Post Shasta, pre-Trinity diversion mean flows are about 200 percent of pre-Shasta, and post Trinity diversion flows are more than 250 percent of pre-Shasta flows. Present summer flows at Red Bluff average 10,860 cfs. Figures 8 to 11 show the hydrologic changes at Vina, Hamilton City, Butte City and Colusa gages only for the post Shasta and post Whiskeytown hydrologic periods because these gages were not in operation prior to Shasta Dam. The summer flows at these gages are lower than at Bend Bridge because of diversions.

### Flow Duration

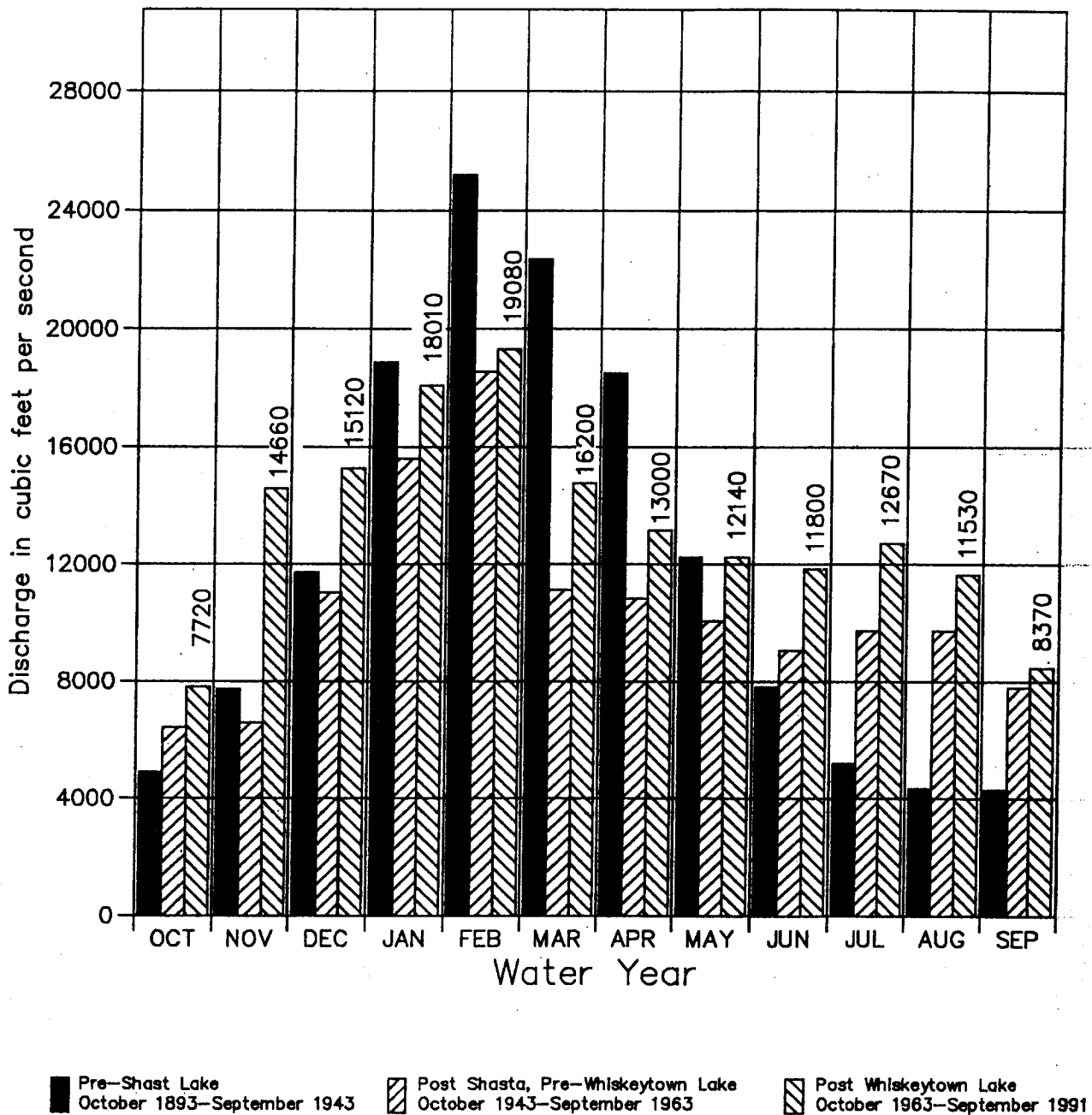
Flow duration curves show the percent of time a specified discharge is equalled or exceeded. A computer program, provided by the USGS, separates all mean daily flows during the study period into 34 classes. The computer then determines the percent of time each flow class was equalled or exceeded. These data are then plotted on log-percent paper.

Figure 12 shows the flow duration curve for the Sacramento River above Bend Bridge and at Vina Bridge for the post Whiskeytown hydrologic period. The graph shows that post Whiskeytown flows exceed 70,000 cfs 1 percent of the time (1 of every 100 days ), 6000 cfs 50 percent of the time, and 2,800 cfs 99 percent of the time. These discharges are lower than one would expect because of the five years of drought between 1986 and 1991. The comparative discharges at the Vina Bridge gage are 90,000, 10,000 and 4,000. The Hamilton City gage, shown on Figure 13, exceedence flows are 80,000 cfs, 9,000 cfs, and 4,200 cfs. Note that on this figure, the low flows are similar for the three downstream gages. Note also that the high flows for the Colusa gage (Figure 13) have considerably lower peaks than the other two gages. This is caused by flood diversions into Moulton and Colusa weirs.

The effect of Shasta and Keswick Dams on the natural flow duration curve has been to:

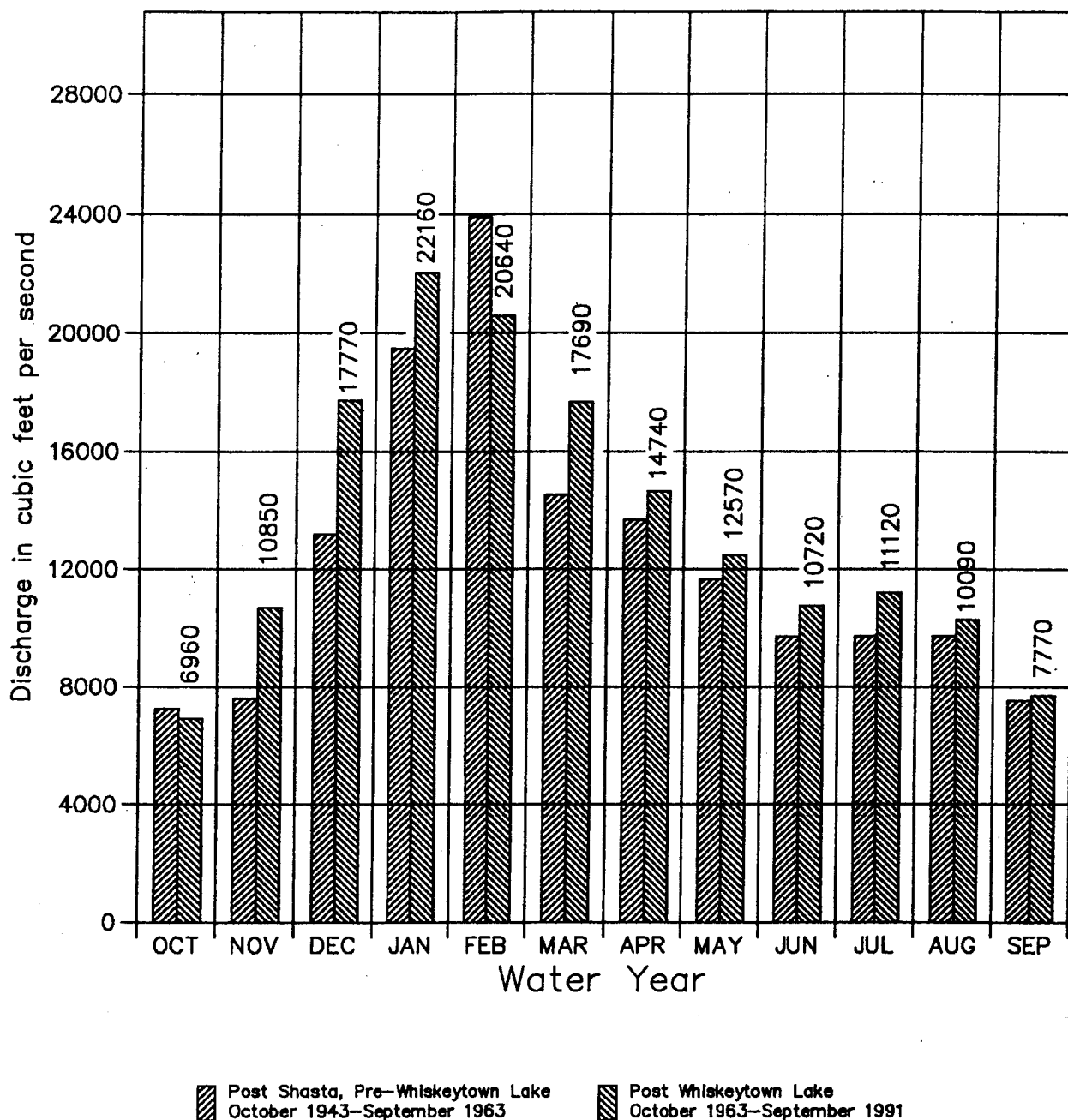
1. Decrease the minimum discharge and increase the number of very low discharges. This occurred in the past when the powerhouse was closed for repairs and before minimum flow releases for fish were mandated.
2. Increase the number of moderate discharges and reduce the number and the volume of very high flows.

Figure 7



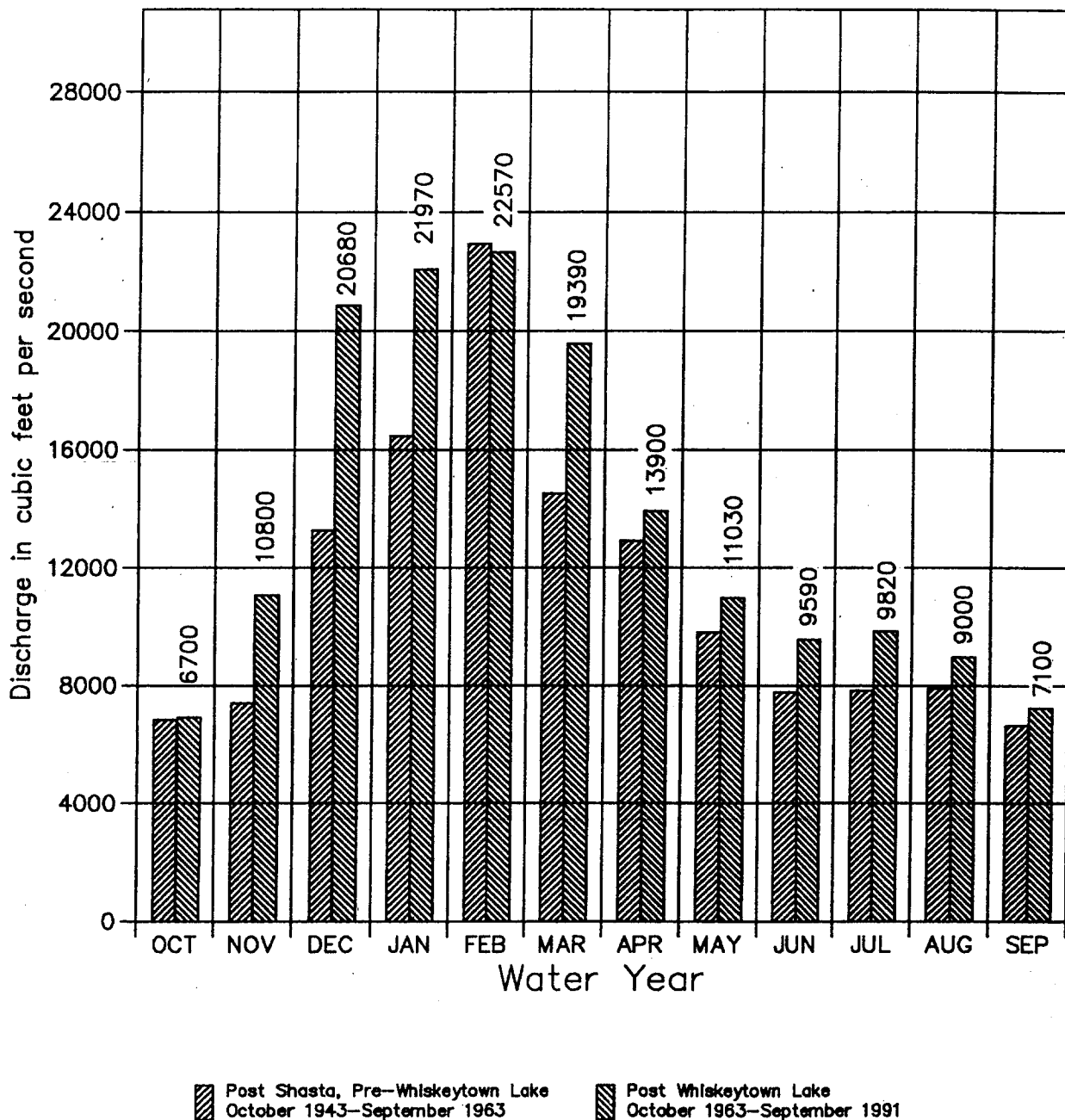
Sacramento River Bank Erosion Investigation  
 Changes in Mean Monthly Discharge  
 Sacramento River Above Bend Bridge

Figure 8



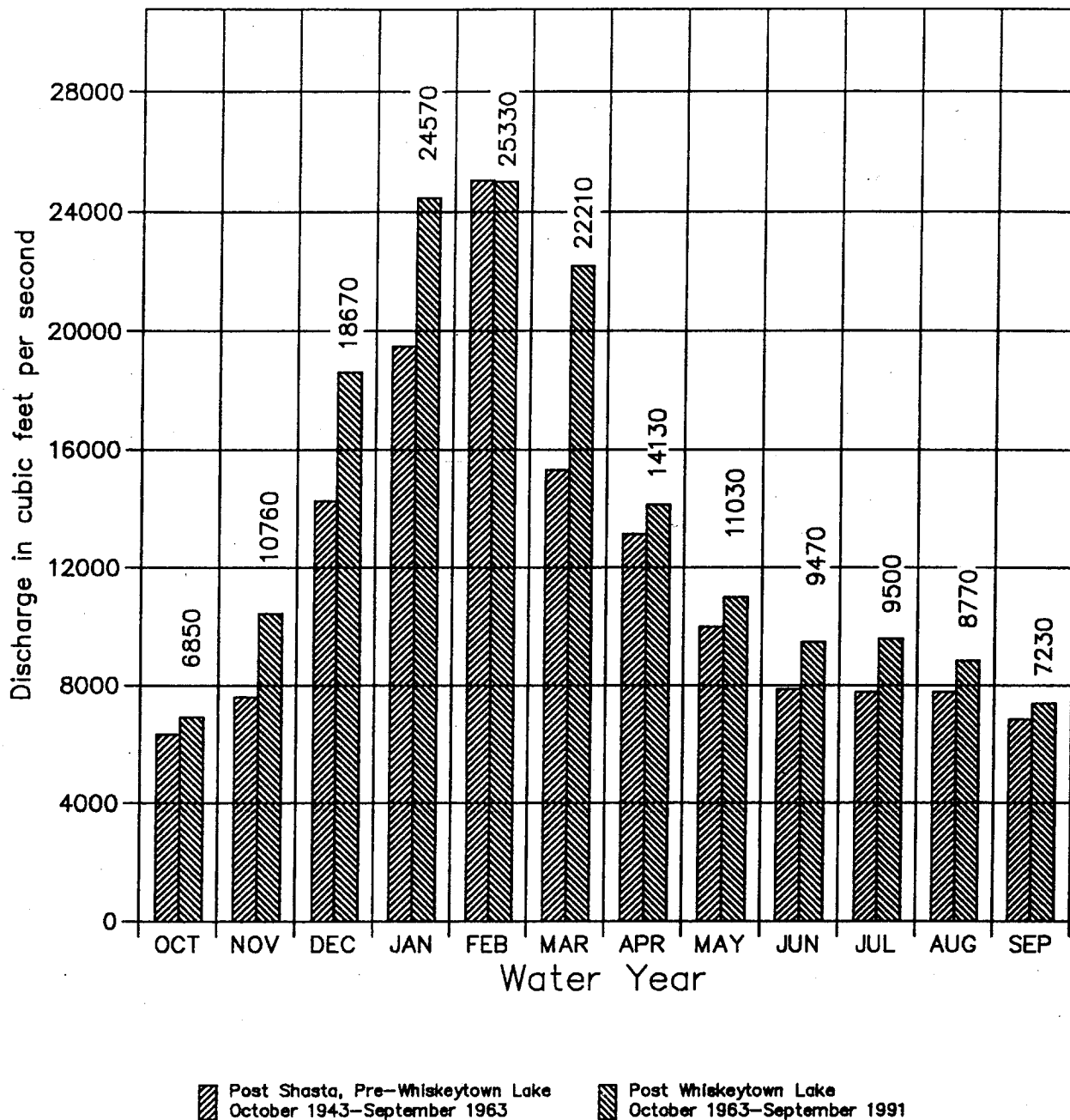
Sacramento River Bank Erosion Investigation  
Changes in Mean Monthly Discharge  
Sacramento River at Vina Bridge

Figure 9



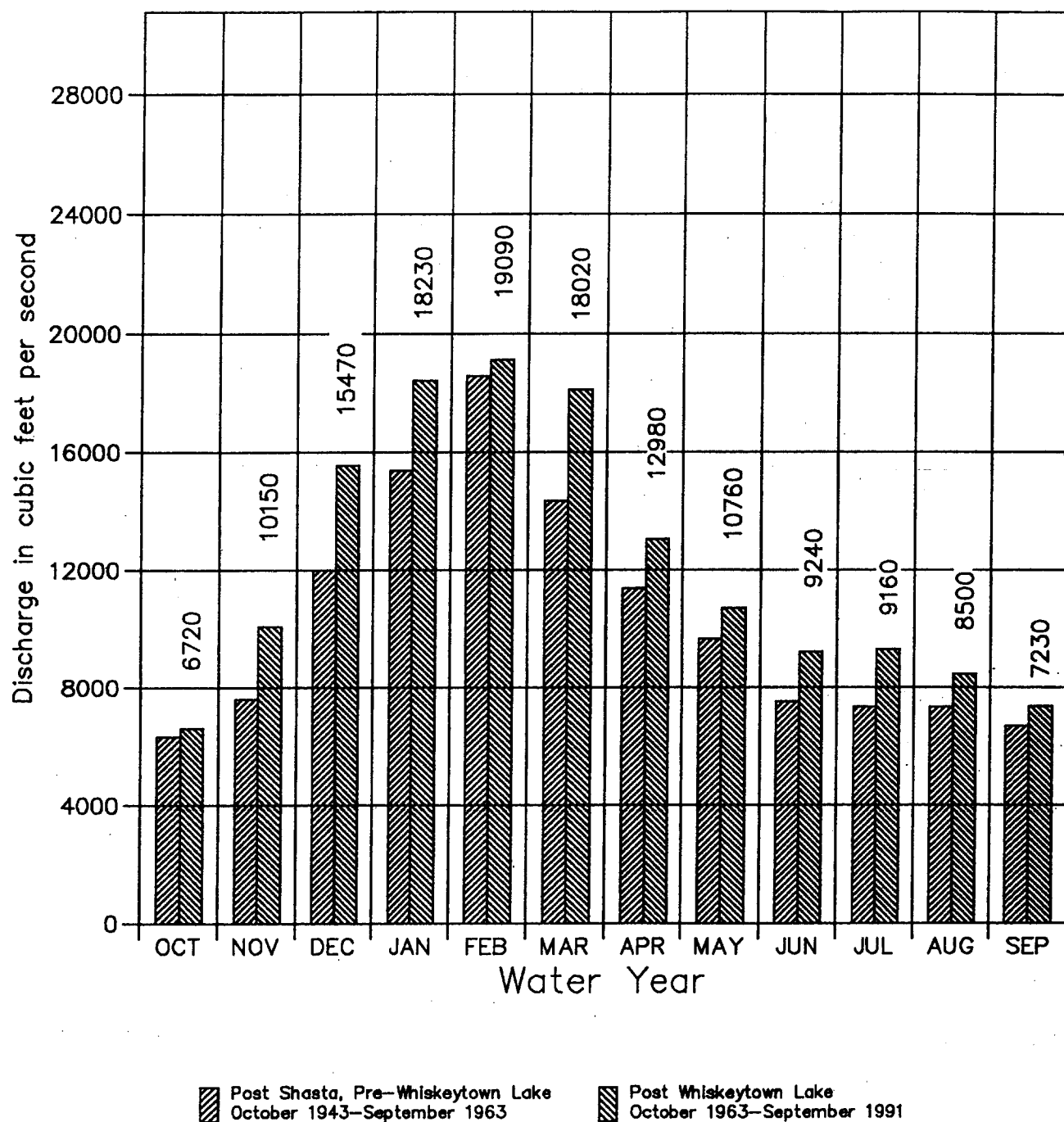
Sacramento River Bank Erosion Investigation  
 Changes in Mean Monthly Discharge  
 Sacramento River at Hamilton City

Figure 10



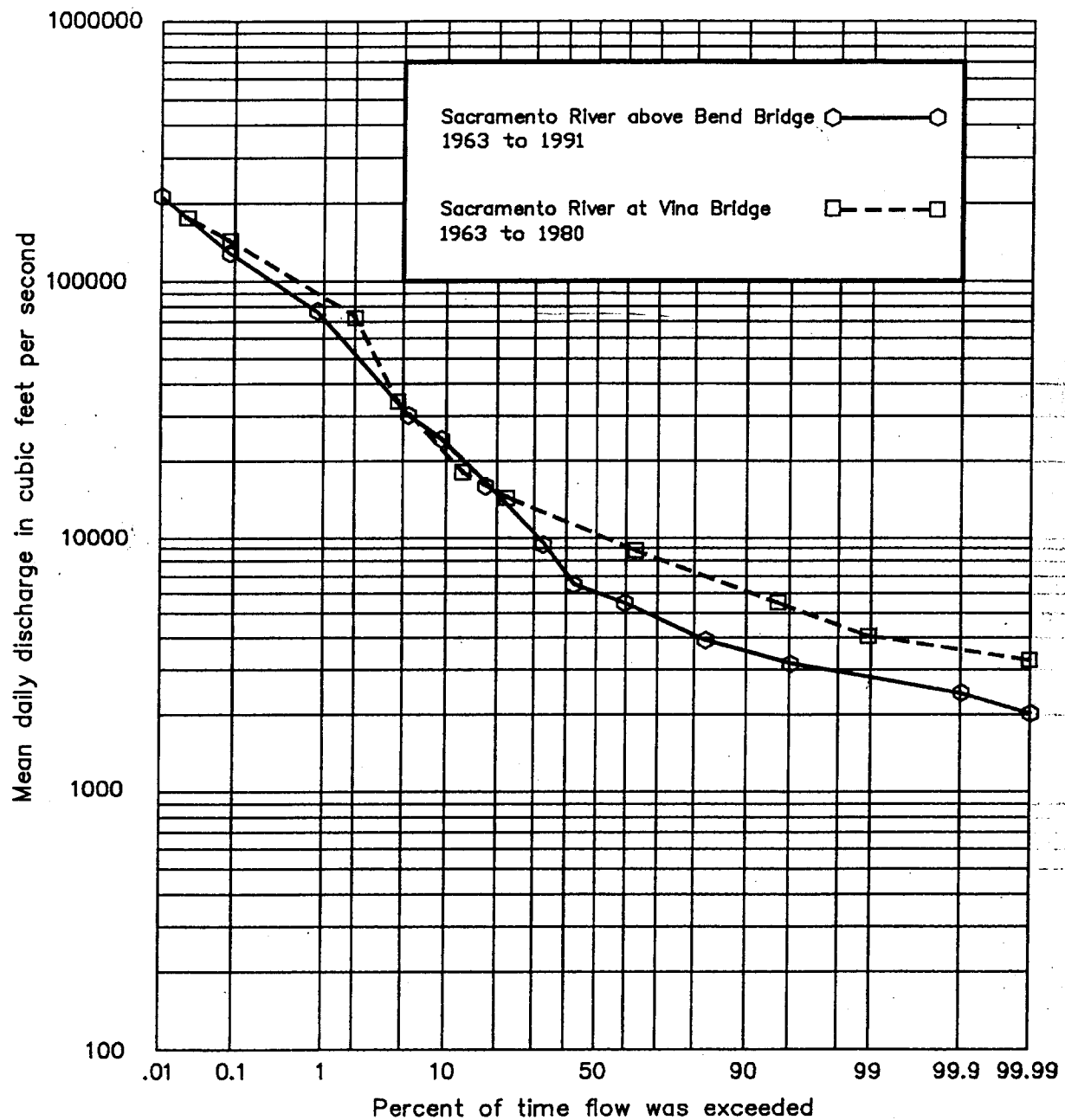
Sacramento River Bank Erosion Investigation  
 Changes in Mean Monthly Discharge  
 Sacramento River at Butte City

Figure 11



Sacramento River Bank Erosion Investigation  
 Changes in Mean Monthly Discharge  
 Sacramento River at Colusa

Figure 12

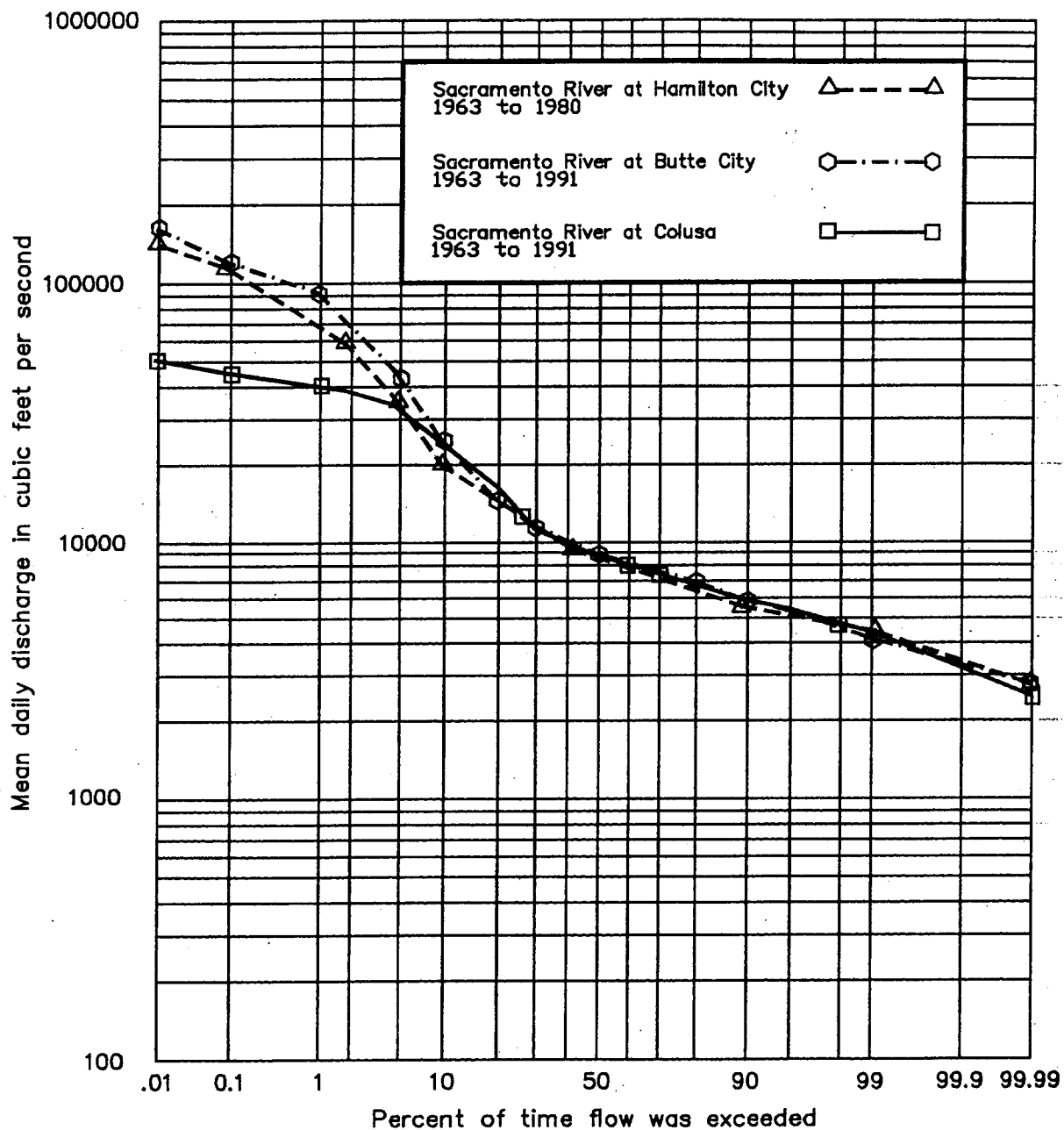


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Sacramento River Bank Erosion Investigation  
Flow Duration  
Sacramento River above Bend Bridge and at Vina Bridge



Figure 13



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Sacramento River Bank Erosion Investigation  
Flow Duration  
Sacramento River at Hamilton City, Butte and Colusa

The effect of the Trinity diversion on post Shasta flows has been to increase the discharge for any particular exceedence frequency. For example, between 1981 and 1991, the average discharge at the Bend Bridge gage has been increased by 1250 cfs, a 26 percent increase.

## **Flood Hydrology**

Peaks in the hydrograph generally occur in response to intense winter rainstorms. Winter flooding from runoff above Red Bluff and in the study area is intensified when the soil mantle is saturated, when the ground is frozen or when warm rain on snow adds snowmelt to runoff. Flooding on the tributary streams is characterized by high peak flows of moderate duration (USCE, 1978).

The flood hydrology of the Sacramento Basin changes in the downstream direction as tributaries combine with the Sacramento River. Before construction of Shasta Dam, the main Sacramento River flood peak formed above Shasta for most storms. Since construction of Shasta, the flood peak is usually generated in the tributaries between Redding and Red Bluff. The tributaries below Red Bluff generally peak before the upstream peak on the Sacramento River arrives and consequently have a lesser effect.

In the few years before construction of Shasta Dam, great floods occurred in 1937, 1940, 1941 and 1942. Table 6 shows the peak flows. The storms of December 1937 were, to that date, the most destructive in the history of Northern California, and the Sacramento River reached its highest level in 42 years. An eyewitness account described the orchards in the Jelly District as completely under water except for the very tops of the trees, and the entire lower portion of Bend was inundated. Many cattle and sheep were lost, and massive amounts of debris from upstream lodged in the study reach. The greatest natural Sacramento River flow of record occurred in 1940 when severe flooding again occurred in the study area. According to the February 29, 1940 edition of the Red Bluff Daily News, floodwater was 2-1/2 feet over the deck of Bend Bridge, and "The Jelly District was under several feet of water as the river there yesterday reached an all-time high of 41 feet, nearly three feet higher than the 1937 flood."

Floods that occurred before Shasta Dam are essentially of historical interest only, but flow conditions and the pattern of inundation during the 1940 flood would be very similar to the flow and the overflow pattern expected during a 100-year flood with Shasta Dam in operation (USCE, 1977).

Flood frequency diagrams are used to predict the number of floods within a specified range of magnitude which could be expected to occur during any long period of time. The magnitude of 10- and 100-year, and other events may be read directly from the graph with the reliability depending on the length of record. The above Bend Bridge near Red Bluff gage has the longest record in Northern California, with 101 years (1892-present).

**TABLE 6 - PEAK FLOWS OF HISTORICAL FLOODS**  
in Thousands of Cubic Feet per Second

Station	12/37	02/40	04/41	02/42	12/51	01/56	02/58	12/64	01/69	01/70	01/74	01/78	02/80	03/83	02/86
Sacramento River above Bend Bridge (11377100)	262	291	157	203	137	115	139	156	92	157	133	106	104	152	134
Red Bank Creek (11378800)	-	-	-	-	-	5.6	-	9.7	9.2	8.7	6.7	9.3	8.4	10.5	-
Antelope Creek (11379000)	-	-	7.9	10.4	6.5	4.1	2.5	9.0	9.4	17.2	8.4	3.0	6.1	-	-
Elder Creek (11380500)	10.7	13.1	14.1	N/R	4.7	2.5	11.3	10.3	3.8	7.2	8.9	5.0	6.7	5.9	-
Mill Creek (11381500)	36.4	11.4	7.3	11	5.3	4.8	2.2	16	12.4	17.1	10.1	3.3	6.7	7.8	11.8
Thomes Creek (11382000)	16.5	17	5.6	8.1	5.7	10.9	11.4	37.8	9.3	18	29.4	7.3	6.7	7.1	32.9
Sacramento River at Vina (11383730)	-	-	-	-	146	135	-	163	139	171	159	121	132	174	-
Deer Creek (11383500)	23.8	18.4	8.0	11	6.7	6.6	8.7	18.8	15	21.1	10.3	4.3	-	11.3	16.1
Sacramento River at Hamilton City (11383800)	-	350	-	-	-	-	-	151	126	156	158	123	-	176	-
Sacramento River at Butte City (11389000)	-	-	-	170	111	149	160	126	120	152	136	121	124	157	145
Sacramento River at Colusa (11389500)	-	-	-	49	39.7	43.2	45.8	-	42.7	48.4	48.6	45.2	45.8	51.8	50.1

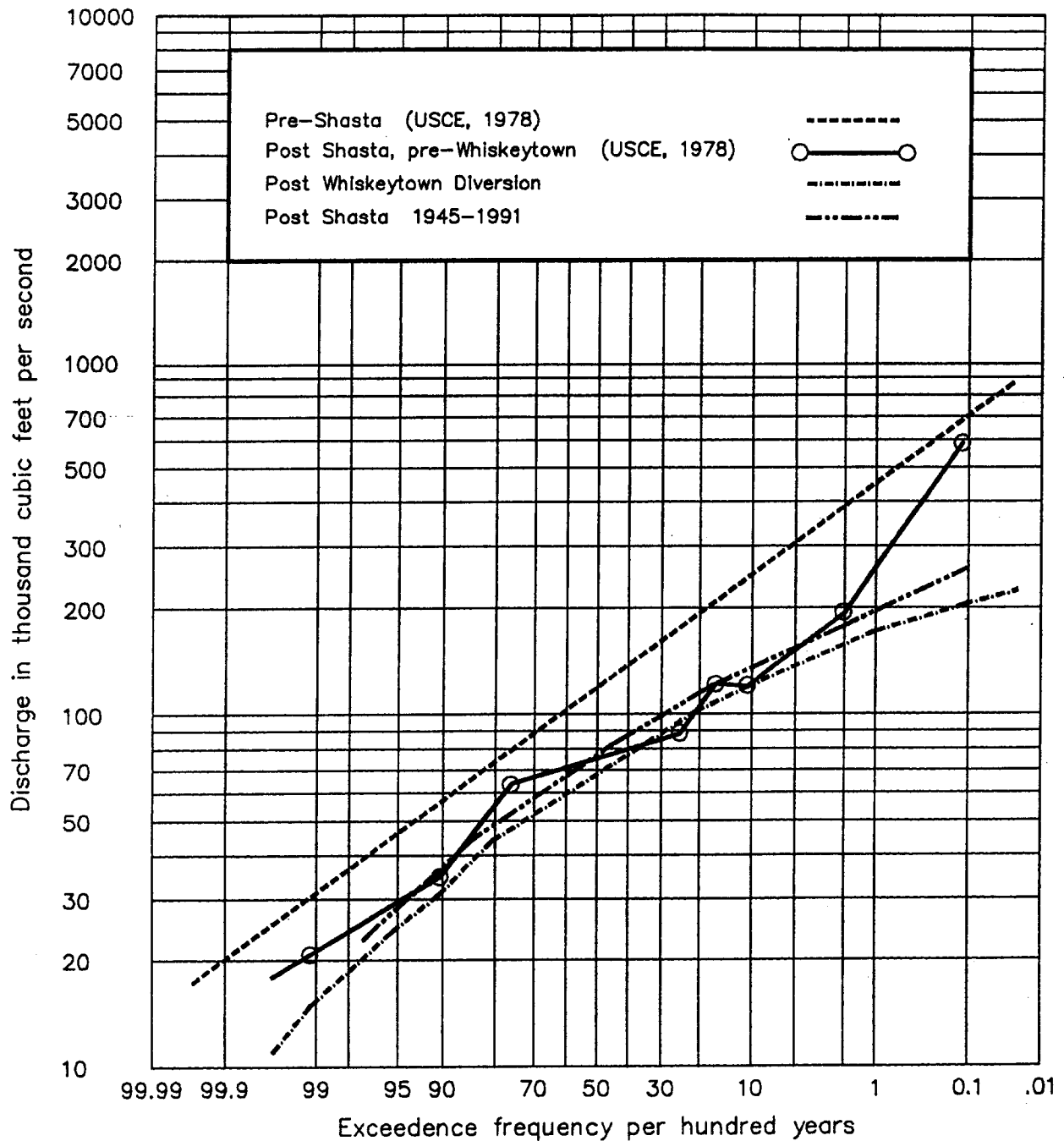
Figure 14 shows the flood frequency curve for the three hydrologic periods at the above Bend Bridge gage. The pre-Shasta Dam and the post Shasta pre-Whiskeytown graphs were calculated by the U.S. Army Corps of Engineers (USCE, 1977) using Log Pearson Type III analysis and by assuming Shasta Dam operations for the entire period of record. The post Shasta graph was derived using Weibull flood frequency analysis on the 45 years of available record. Note the large discrepancy at higher flows between the post Shasta, pre-Whiskeytown and post Whiskeytown hydrologic periods. The flows with a recurrence interval of 100 years and more were calculated by the USCE by assuming the operation of Shasta Dam for the entire period of record. The post Shasta curve was calculated using actual flows. The 1945-1991 graph is probably the best since it has the longest period of record, and the Whiskeytown diversion does not affect floodflows. This graph indicates that a peak with a 2-year recurrence interval has a flow of 79,000 cfs, a 10-year peak of 125,000 cfs and a 100-year of 200,000 cfs.

The effect of Shasta Dam under normal operating conditions is greatest on flood peaks near Keswick. The 100-year flood of 300,000 cfs at Keswick is reduced to 26 percent of the natural flow (DWR, 1984). Shasta Lake is not nearly as effective at controlling higher peak flows downstream because of tributary inflow. The uncontrolled 100-year flood at Red Bluff is 420,000 cfs. This flow would be reduced to 66 percent (277,000 cfs) of the natural flow by the dam. The uncontrolled flows at Vina, Hamilton City, Butte City and Colusa are not known because pre-dam data are not available.

Figures 15 and 16 show the same for the Vina and Hamilton City gages. At Vina Bridge the equivalent 2-, 10- and 100-year peak storm flows are 90,000 cfs, 135,000 cfs, and 205,000 cfs, and at Hamilton City the flows are 90,000, 135,000 and 200,000 cfs. Figure 17 shows the flood frequency curves for the Butte City and Colusa gages. For the Butte City gage the storm flows are 90,000, 128,000 and 185,000 cfs. The equivalent Colusa gage flows are 36,000, 47,000 and 57,000 cfs. Note that overbank flow is not gaged and does not show up on the flood frequency curves.

Figure 14

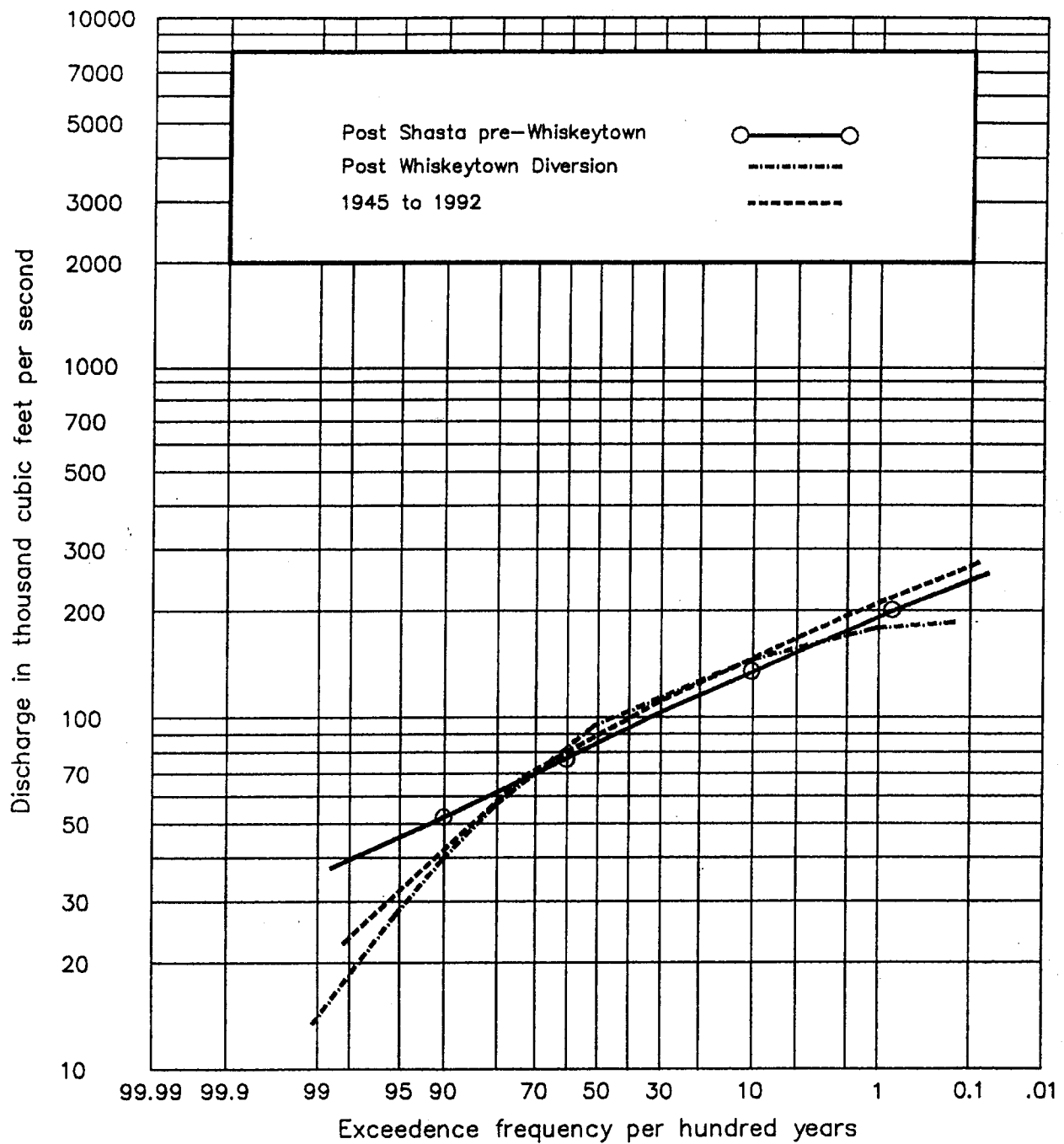
Note: See Table 5 for source and period of record



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NORTHERN DISTRICT

Sacramento River Bank Erosion Investigation  
Peak Flood Flow Frequency  
Sacramento River above Bend Bridge

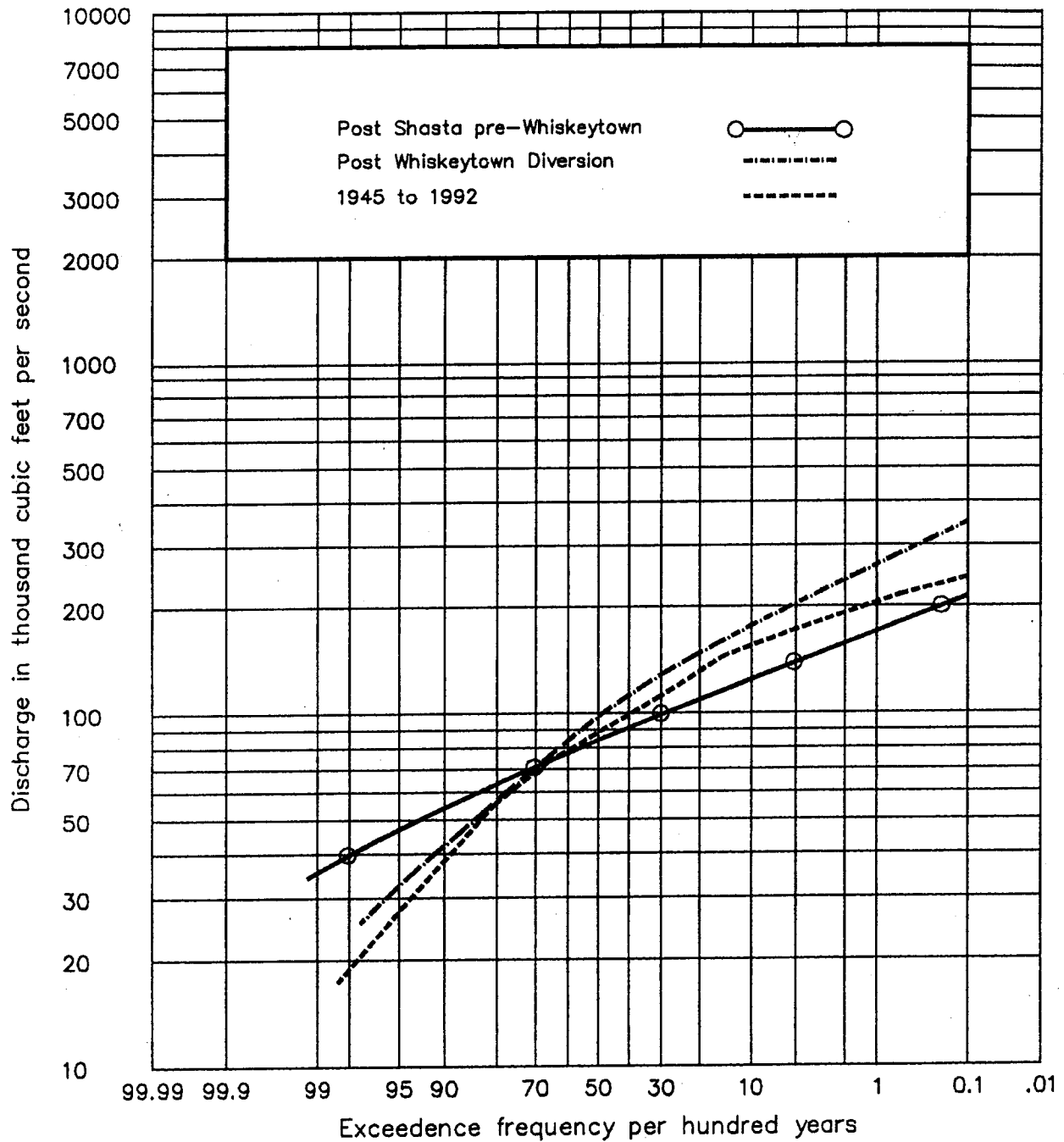
Figure 15



STATE OF CALIFORNIA  
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DEPARTMENT OF WATER RESOURCES  
NORTHERN DISTRICT

Sacramento River Bank Erosion Investigation  
Peak Flood Flow Frequency  
Sacramento River at Vina Bridge

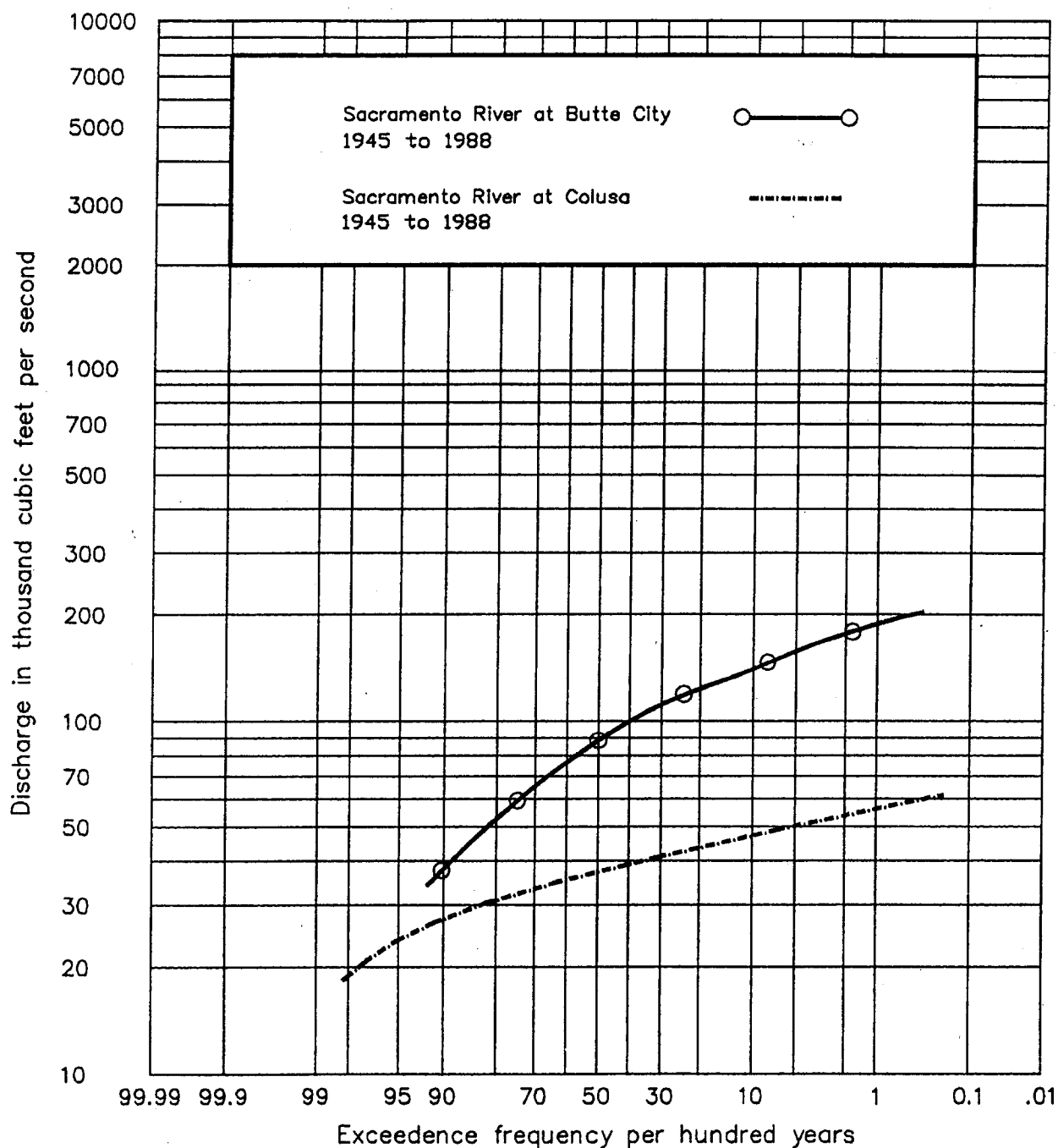
Figure 16



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THE RESOURCES AGENCY  
DEPARTMENT OF WATER RESOURCES  
NORTHERN DISTRICT

Sacramento River Bank Erosion Investigation  
Peak Flood Flow Frequency  
Sacramento River near Hamilton City

Figure 17



STATE OF CALIFORNIA  
THE RESOURCES AGENCY  
DEPARTMENT OF WATER RESOURCES  
NORTHERN DISTRICT

Sacramento River Bank Erosion Investigation  
Peak Flood Flow Frequency  
Sacramento River at Butte City and Colusa



## **PART III: EROSION AND DEPOSITION OBSERVATIONS**

SACRAMENTO RIVER BANK EROSION  
FLOODPLAIN DEPOSITION  
LAKE RED BLUFF DEPOSITION  
GAGING STATION CROSS SECTIONS  
THALWEG DEPTHS AND RIVER WIDTHS

## SACRAMENTO RIVER BANK EROSION

A river erodes both its banks and bed. Bed erosion leads to degradation and grading of the stream profile. In a bedrock stream, this process is relatively slow, even during periods of geologically rapid rejuvenation and uplift. In alluvial river systems, banks erode and sediments are deposited. Floodplains, islands, and side channels will undergo modification with time. Bed erosion also occurs in alluvial streams, but the erosion is generally balanced by deposition over a period of years.

Bank erosion is generally of much more interest and concern to people. Bank erosion is dependent on channel shape, bed and bank material, and river hydraulic characteristics. Because of the generally stable banks of the Sacramento River between Keswick and Red Bluff, bank erosion is slight in most places. Between Red Bluff and Colusa, however, significant bank erosion occurs. Downstream of Colusa, flood flows and associated velocities are greatly reduced by overflow occurring upstream (both overbank flow and flow at the Moulton and Colusa overflow weirs). In addition, downstream the flatter slopes of the channel bed minimize the erosion potential.

Bank erosion generally occurs on the outside of meander bends. Here, banks are susceptible to erosion because high-flow velocities impinge directly into banks and turbulent motion along the channel thalweg undercuts the banks. Eroding banks may be either high-terrace or low terrace. High terrace banks normally have a deep soil profile containing mostly loamy sand and silt. Below the soil is a thicker deposit of sand and gravel. A low-terrace bank consists mostly of a sand and gravel with a thin silt profile on top.

The fish, wildlife, and riparian vegetation are adjusted to the cycle of erosion, deposition and changing channel pattern in which the river swings slowly back and forth across a broad meander belt. The health and productivity of the system at any one point is dependent on the periodic rejuvenation associated with these changes.

Salmon prefer to spawn in fresh, uncompacted gravel that has recently moved. These spawning beds tend to occur in wide, shallow riffle areas such as areas with multiple channels or chute cutoffs. Salmon spawn here because of increased flow velocity, shallower depths and greater hydraulic diversity. Gravel in the lower horizons of an eroding bank provides fresh gravel to spawning beds. Between Red Bluff and Colusa, bank erosion is estimated to contribute about 85 percent of the total available spawning gravel (DWR 1984; 1985). Much of the sand and silt from the soil horizon is redeposited in the riparian forests downstream.

Bank erosion is also the driving force for riparian plant succession. On the outside of bends, high-terrace banks with a mature forest typically consisting of valley oak, box elder, and black walnut are eroded. On the opposite side is a point bar consisting of sand and gravel. Willows, alders and cottonwoods become established here. The rapid invasion of riparian vegetation

slows flood flow velocities and allows sand and silt to deposit. With time, riparian stages with a succession of different plant species occurs as the point bar becomes higher and farther away from the river.

Various birds and other wildlife use different riparian stages for feeding, nesting, and reproduction. The climax valley oak forests are relatively sterile compared to the younger riparian stages. Therefore, bank erosion and riparian rejuvenation are necessary to maintain a healthy and productive ecosystem.

Sediment deposition is inextricably linked to bank erosion. Without deposition, the channel would simply widen until it was so large that erosion would terminate. However, the coarser material eroded from the bank is deposited on point bars downstream. The point bars constrict the bend and enable erosion to continue.

DWR (1979) observed bank erosion over a 2-1/2-year period at six sites in the Red Bluff-to-Colusa reach. Bank erosion was divided into summer (low-flow) erosion and winter (high-flow) erosion. Only two of the six sites showed any erosion during the summer. Average bank recession between April and October 1977 was 11.4 and 2.2 feet, respectively.

In contrast, high flows were far more conducive to erosion. A major storm occurred in January 1978. Erosion was greatest during the period that included this storm, with bank recession ranging from 30 to 50 feet. During the storm itself, Woodson Bridge State Recreation Area below Thomes Creek lost over 40 feet in a single 24-hour period.

Our bank erosion study was divided into two phases. The Phase I- Aerial Photography Bank Erosion Study identified 67 eroding bank sites between Red Bluff and Ord Ferry. The amount of erosion at these sites over a 11-year period (1976-1987) were measured using aerial photography. In the Phase II-Bank Erosion Monitoring Sites Study, we surveyed 15 eroding bank sites between 1986 and 1993 in the reach from Red Bluff to Colusa. These are resurveyed semi-annually.

### **Phase I-Aerial Photography Bank Erosion Study**

The purpose of this phase of the study was to determine total bank erosion, bank composition, gravel and silt produced from bank erosion, and bank recession rates. A total of 67 bank erosion sites were identified and evaluated by comparing 1976 and 1987 aerial photographs. All visibly eroded areas from Red Bluff to Ord Ferry were measured using a planimeter.

Of the 67 identified eroding banks between Ord Ferry and Red Bluff, 30 were sampled. Three bulk gravel samples were taken near the middle of the eroding bend to estimate gravel size distributions in the lower bank. One bulk sample was obtained at the toe of the bank near the summer waters edge, another approximately halfway up to the top of the gravel-floodplain

contact, and the last just below this contact. No samples were taken of overlying silt and sand floodplain deposits.

The three samples were combined and mechanically sifted in the field and each fraction weighed. Fractions less than 0.375 inch sieve size were brought back to the office for further analysis. At each site, about 400-600 pounds of gravel were sifted and weighed. Weights of sediment fractions were noted on a data analysis sheet and these data in turn were plotted on an Autocad-generated mechanical analysis diagram, shown in Appendix A.

Eroded bank sediment volumes were determined by measuring bank heights and lengths, area of the bank eroded, and gravel thicknesses. Bank heights (defined as the distance from the bottom of the river thalweg to the top of the bank) and gravel thicknesses were measured using a combination of sonar measurements and stadia and level measuring. Bank lengths were measured using a tape along the bank edge, and the distances from bank edge to the top of the gravel layer were obtained. Gravel thickness was assumed to extend from the top of the gravel layer to the bottom of the thalweg.

Eroded bank areas were determined by overlaying 1987 aerial photos of the channel on 1976 aerial photos and measuring the change in river bank location using a planimeter. Bank lengths and maximum bank recession were also measured on the photos. Data from the surveyed sites were averaged by geomorphic reach and applied to the unsurveyed sites.

Table 7 is a summary of bank erosion data for the Red Bluff to Ord Ferry reach during this 11-year period. In general, there are a number of observations that can be made from this table. The average bank height from the bottom of thalweg to the top of the bank is about 25 feet, with 16 feet of gravel and 9 feet of silt. The average eroding bank cross-section between Red Bluff and Ord Ferry is shown pictorially in Figure 18.

The average bank recession of an actively eroding bank is about 20 feet per year, ranging from a few feet to nearly 80 feet. The average length of a contiguous eroding bank is about 3,000 feet, for a total of about 197,000 linear feet in this reach. This represents 34 percent of the bank. Another 18 percent was eroding but has been protected with riprap. More specific observations include:

- The mean bank height in 1987 was 25.1 feet, ranging from a minimum of 15.4 feet to a maximum of 33.7 feet. Two banks were higher, at 40.2 and 47.9 feet but these banks are composed of Pliocene Modesto Formation and not recent gravel deposits.
- The mean gravel thickness in 1987 was 16.1 feet, ranging from a minimum of 6.0 feet to a maximum of 23.7 feet. Two greater gravel thicknesses occur but these are Pleistocene Modesto Formation deposits.
- The mean eroded bank area per site is 802,000 square feet, ranging from a minimum of 32,000 square feet to a maximum of 3,140,000 square feet.

- The average per site gravel volume eroded is 429,200 cubic yards, ranging from a minimum of 16,800 cubic yards to a maximum of 2,028,400 cubic yards.
- The average per site volume of fines eroded is 294,000 cubic yards, ranging from a minimum of 4,400 cubic yards to a maximum of 2,228,900 cubic yards.
- The average per site total bank volume eroded is 723,200 cubic yards, ranging from a minimum of 24,500 cubic yards to a maximum of 3,118,000 cubic yards.
- The average length of an eroding bank from 1976-1987 is 2,939 feet, ranging from a minimum of 620 feet to a maximum of 8,860 feet.
- The average per site maximum bank recession is 443 feet, ranging from a minimum of 40 feet to a maximum of 1,280 feet.
- The average per site total bank recession is 235 feet, ranging from a minimum of about 30 feet to a maximum of 830 feet.
- The average annual bank recession from 1976 to 1987 is 21.4 feet, ranging from a minimum of 2.7 feet to a maximum of 75.2 feet.

## **Phase II-Bank Erosion Monitoring Sites Study**

Beginning in 1986, ten bank erosion monitoring sites were surveyed using a theodolite and an electronic distance meter. Six more were added in 1988, for a total of sixteen sites. Each site is surveyed twice yearly. Successive bank lines are plotted and the eroded bank area calculated. The Phelan Island and Golden State Island sites were riprapped during the summer of 1988 and are no longer monitored. The sixteen sites are shown on Figure 19 and described in order from upstream to downstream.

### Coyote Creek

Coyote Creek is at River Mile 232.5, on the west bank, about one mile above Mill Creek. Plate 7 shows the Coyote Creek erosion site. The upstream two-thirds of this site is high terrace cultivated fields and orchards, and the lower third is low terrace riparian vegetation. The bank is fairly straight, except for a sharply curved lower third of the site.

The downstream third of the area is underlain mostly by silt, versus sand and gravel overlain by silt and sand for the upstream two-thirds of the site.

TABLE 7

SACRAMENTO RIVER EROSION SITE PARAMETERS, RED BLUFF DIVERSION DAM TO ORD FERRY 1975 TO 1986

REACH	EROSION SITE***	RIVER MILE	AVERAGE BANK HEIGHT (FEET)	AVERAGE GRAVEL THICKNESS (FEET)	ERODED BANK AREA (SQUARE FEET X 1,000)	TOTAL GRAVEL VOLUME ERODED (CUBIC YARDS X 1,000)	TOTAL FINE VOLUME ERODED (CUBIC YARDS X 1,000)	TOTAL BANK VOLUME ERODED (CUBIC YARDS X 1,000)	LENGTH OF ERODED BANK (FEET)	MAXIMUM BANK RECESSION (FEET)	AVERAGE BANK RECESSION (FEET)	AVERAGE ANNUAL BANK RECESSION (FEET)
	ERODING BANK	240.5	20.7*	14.2*	336	176.7**	80.9**	257.6**	3680	160	91.3	8.3
	SACT 1	239.9	21.1	13.7	236	119.7	64.7	184.4	1770	240	133.3	12.1
6A	ERODING BANK	239.5	20.7*	14.2*	141	74.2**	33.9**	108.1**	1960	160	71.9	6.5
	ERODING BANK	239.0	20.7*	14.2*	63	33.1**	15.2**	48.3**	1280	80	49.2	4.5
	ERODING BANK	239.0	20.7*	14.2*	32	16.8**	7.7**	24.6**	800	100	40.0	3.6
	SACT 2	238.5	20.3	14.7	742	404.0	153.9	557.9	3360	620	220.8	20.1
	ERODING BANK	237.0	19.9*	13.1*	3140	1519.6**	798.6**	2318.2**	5640	800	556.7	50.6
	SACT 3	236.5	16.4	12.0	485	215.6	61.1	276.6	3200	228	151.6	13.8
	ERODING BANK	236.0	19.9*	13.1*	96	46.5**	24.4**	70.9**	1090	135	88.1	8.0
	ERODING BANK	235.5	19.9*	13.1*	85	41.1**	21.6**	62.8**	1100	100	77.3	7.0
6B	SACT 4	235.0	23.3	13.2	1614	789.1	603.8	1392.8	4800	700	336.3	30.6
	ERODING BANK	234.0	19.9*	13.1*	666	321.8**	169.1**	491.0**	4520	240	147.1	13.4
	ERODING BANK	233.0	19.9*	13.1*	263	122.4**	64.3**	186.8**	1860	190	136.0	12.4
	SACT 5	232.9	21.1	14.0	468	242.7	123.1	365.7	3530	400	132.6	12.1
	ERODING BANK	232.0	19.9*	13.1*	96	46.5**	24.4**	70.9**	970	200	99.0	9.0
6C	ERODING BANK	231.5	19.9*	13.1*	371	179.5**	94.4**	273.9**	2220	320	167.1	15.2
	ERODING BANK	231.0	19.9*	13.1*	193	93.4**	49.1**	142.5**	1514	250	127.5	11.6
	SACT 6	228.9	33.9	16.9	144	90.1	90.7	180.9	2480	88	58.1	6.3
	ERODING BANK	227.5	27.2*	15.4*	786	447.3**	345.5**	792.8**	3840	460	204.7	18.6
	ERODING BANK	226.0	27.2*	15.4*	645	367.1**	283.5**	650.6**	3960	360	162.9	14.8
	SACT 7	225.5	30.7	14.8	44	24.1	25.9	50.0	1480	40	29.7	2.7
	SACT 8	224.4	20.8	19.9	131	96.6	4.4	100.9	2220	136	59.0	5.4
	SACT 9	223.3	26.8	14.2	264	138.8	123.2	262.0	3400	144	77.6	7.1
6D	ERODING BANK	223.0	27.2*	16.4*	605	344.3**	266.9**	610.2**	1980	560	306.6	27.8
	TOOMBS 1 & 2	222.0	27.0	7.7	3118	889.2	2228.8	3118.0	5100	1080	611.4	55.6
	ERODING BANK	221.7	27.2*	16.4*	226	129.8**	100.2**	230.0**	1950	210	116.9	10.6
	SACT 28	221.3	24.4	20.5	407	309.0	58.8	367.8	2260	480	180.1	16.4
	ERODING BANK	221.0	27.2*	16.4*	257	146.3**	113.0**	259.2**	1900	260	135.3	12.3
	PALISADES	219.0	33.7	15.1	633	364.0	436.1	790.1	2880	440	219.8	20.0
6E	ERODING BANK	217.5	27.2*	16.2*	155	93.0**	63.1**	156.1**	1740	110	89.1	8.1
	ERODING BANK	216.0	27.2*	16.2*	1893	1136.8**	771.2**	1907.0**	8860	870	213.7	19.4
	SACT 12	213.1	19.0	6.4	1968	466.6	918.4	1384.9	2380	1280	826.9	75.2
	SACT 13	212.5	28.4	13.9	624	321.2	335.1	656.4	920	1280	678.3	61.7
	SACT 10	211.9	21.0	16.8	430	267.6	66.9	334.4	2360	312	183.0	16.6
	SACT 14	211.2	20.9	11.0	1469	598.5	538.6	1137.1	5100	620	288.0	26.2
	SACT 16	210.6	30.4	23.7	1161	1019.1	288.1	1307.2	3000	760	387.0	36.2
	SACT 16	210.4	23.9	13.6	1476	743.5	563.1	1306.5	4750	568	310.7	28.2
6F	ERODING BANK	209.0	27.1*	17.0*	547	343.8**	206.8**	549.6**	4620	240	118.4	10.8
	ERODING BANK	208.0	27.1*	17.0*	251	157.8**	94.5**	252.2**	1710	225	146.8	13.3
	SACT 17	207.2	40.2	35.0	41	53.1	7.9	61.0	620	120	66.1	6.0
	ERODING BANK	207.0	27.1*	17.0*	511	321.2**	192.3**	513.5**	2500	300	204.4	18.6
	ERODING BANK	206.0	27.1*	17.0*	401	262.0**	150.9**	402.9**	1850	330	216.8	19.7
	SACT 18	204.2	23.3	20.2	330	246.9	37.9	284.8	2660	220	124.1	11.3
	SACT 19	203.2	31.5	7.3	144	38.9	129.1	168.0	1700	140	84.7	7.7
	ERODING BANK	203.0	27.1*	17.0*	2333	1466.3**	877.9**	2344.2**	5220	1225	446.9	40.6
	ERODING BANK	202.0	27.1*	17.0*	610	383.4**	229.5**	612.9**	2500	375	244.0	22.2
	SACT 20	201.5	32.7	21.8	1236	997.1	498.6	1496.7	3230	600	382.4	34.8
6G	ERODING BANK	201.0	27.1*	17.0*	169	106.2**	63.6**	169.8**	1360	220	124.3	11.3
	ERODING BANK	199.0	26.5*	19.1*	245	173.3**	87.1**	260.5	1900	215	128.9	11.7
	ERODING BANK	198.0	25.8*	21.2*	188	147.3**	32.4**	179.6**	2000	170	94.0	8.5
	ERODING BANK	196.0	25.8*	21.2*	1074	641.3**	185.0**	1026.3**	2580	695	416.3	37.8
	ERODING BANK	195.5	25.8*	21.2*	1110	869.5**	191.2**	1060.7**	2970	840	373.7	34.0
6H	ERODING BANK	195.5	25.8*	21.2*	1220	955.7**	210.1**	1165.8**	2560	680	476.6	43.3
	ERODING BANK	194.5	25.8*	21.2*	682	534.2**	117.5**	651.7**	2820	475	241.8	22.0
	SACT 21	194.0	23.3	21.9	294	238.5	16.2	253.7	2220	220	132.4	12.0
	ERODING BANK	193.5	25.8*	21.2*	285	223.3**	49.1**	272.3**	1800	220	158.3	14.4
	SACT 24	193.0	28.3	20.4	576	435.2	166.5	603.7	2820	320	204.3	18.6
	ERODING BANK	192.0	22.8*	12.1*	2321	1040.2**	918.1**	1958.2**	5810	520	399.5	36.3
	PHELAN ISL	191.5	27.0	6.5	1955	470.6	1484.4	1955.0	4620	920	423.2	38.5
	GOLDEN STATE	190.0	26.0	6.0	1598	355.1	1183.7	1538.8	4080	652	391.7	35.6
7A	ERODING BANK	190.0	22.8*	12.1*	439	196.7**	173.6**	370.4**	3195	250	137.4	12.5
	SACT 23	189.0	47.9	43.7	102	165.1	16.9	181.0	1200	300	86.0	7.7
	SACT 25	187.7	21.9	13.6	1440	725.3	442.7	1168.0	3980	576	361.8	32.9
	ERODING BANK	187.0	22.8*	12.1*	1707	765.0**	675.2**	1440.2**	3400	1000	502.1	45.6
	ERODING BANK	187.0	22.8*	12.1*	2616	1172.4**	1034.8**	2207.1**	4200	1070	622.9	56.6
	SACT 26	186.5	21.4	21.0	2608	2028.4	38.6	2067.1	5800	1200	449.7	40.9
	R. D. FARWELL	186.5	17.6	13.4	1284	627.3	196.6	823.9	5140	500	245.9	22.4
TOTAL			1678.4	1076.7	53750	28755.7	19698.0	48453.8	196909	29699	15768.0	1433.6
AVERAGE			26.1	16.1	802	429.2	294.0	723.2	2939	443	235.3	21.4

\* MEAN VALUES OF SURVEYED DATA BY GEOMORPHIC REACH

\*\* GENERATED FROM MEAN VALUES OF SURVEYED DATA

\*\*\* LOCATIONS IDENTIFIED BY RIVER MILE

SACT 1-26 ARE BULK GRAVEL SAMPLE LOCATIONS, SHOWN IN APPENDIX A

Plate 4 shows that the site has had about 1,500 feet of erosion in the last 100 years. Over the long-term, erosion has progressed westward at an average rate of 15 feet per year at the center of the site, although only minor erosion has occurred here since 1946. Several hundred feet of private riprap is in the bend above the site.

The river has not occupied the eroding high terrace bank in the last 100 years, although there is some subtle evidence of meander scrolls and channel deposits several thousand feet west of the present bank. The east bank consists of gravel point bar deposits. Plate 1 shows that about 1,000 feet downstream, the east bank is constrained by a cemented volcanic gravel mapped as Upper Modesto Formation by Helley and Harwood (1985).

The bank's radius of curvature is about 3,700 feet. Average bank erosion between June 1988 and August 1993 is 11 feet. The maximum erosion occurred at the sharply curved lower end, where 19 feet of recession occurred between November 1992 and August 1993. Only a few feet of recession occurred along the straight upper stretch.

#### Toomes Creek # 1

This site is at River Mile 222 on the east bank, about 4 miles upstream from Woodson Bridge, as shown on Plate 8. The mouth of Toomes Creek is at the upstream end of the site. Toomes #1 and #2 have a bend radius of curvature of about 2,500 feet. The entire bank area is planted with field crops. The west bank consists of low terrace gravel point bar deposit.

The eroding eastern bank consists of well consolidated clayey silty sand and clayey silt. Plate 4 shows that the one-hundred year meander belt is only about 2,000 feet wide. The Middle Sacramento River Spawning Gravel Atlas (DWR, 1984) shows that the 1896 river channel bifurcated in this area, with the eastern channel about 200 west of the present channel bank. Most of the erosion has occurred since 1969, with about 200 feet of eastward migration. There are no obvious channel features visible on aerial photographs in this area.

Toomes Creek #1 is on the upper end of a long sweeping curve. Only minor erosion has occurred here, with the maximum erosion at less than 4 feet between August 1986 to November 1992. However, between November 1992 and August 1993, a maximum 9 feet and an average 5 feet of bank recession occurred. Plate 1 shows the site geology. The eroding bank was mapped as Upper Modesto Formation by Helley and Harwood (1985). This would explain the slow rate of erosion.

#### Toomes Creek # 2

This site is a continuation of Toomes Creek # 1 and was considered to be a single site for the calculation of the radius of curvature. Plate 9 shows that erosion only occurred on the upstream half of the site. The lower half is in a slough area at low flows. Row crops and fallow grasslands are the predominant overbank vegetation. The bank profile is complex, consisting of

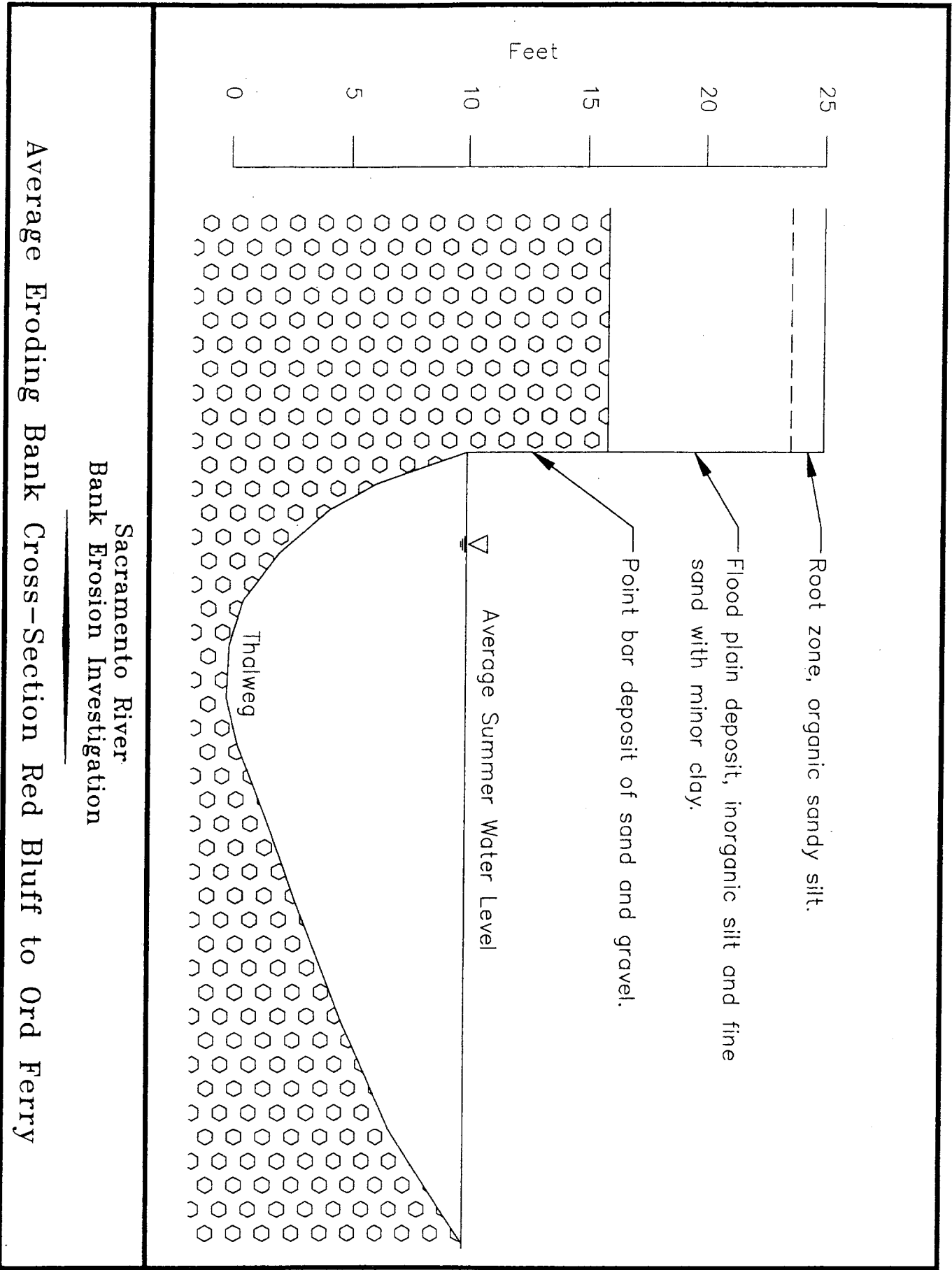
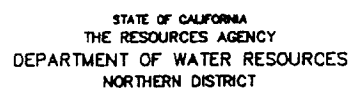


Figure 18



STUDY  
AREA



Sacramento River Bank Erosion Investigation  
Erosion Site Locations  
Sacramento River from Red Bluff to Colusa

a silt layer, underlain by a silty sand, underlain by a sandy gravel. Some of the bank layers extend further out into the river indicating that they are more resistant to erosion.

The bank was surveyed between August 1986 and December 1993. Most of the erosion occurred between stakes 6 and 9. Maximum erosion was at stake 8, with 46 feet of recession. Only minor erosion occurred on the upper and lower parts of the site.

### Palisades

The Palisades erosion site, shown on Plate 10, is about one-half mile upstream of Vina Bridge on the southeast bank, in Woodson Bridge State Recreation Area. It was surveyed between August 1986 and November 1993. The Palisades bank protection method was installed along the eroding bank in the summer of 1986 before the surveying began. The area above the park has been unstable, with a 100-year meander belt of about 5,000 feet. Bank protection was installed directly above the erosion site in 1963. Plate 1 shows the west bank directly below the site is controlled by Tehama Formation overlain by (Upper) Riverbank Formation. This bank has not moved significantly in the last 100 years.

Plate 4 shows that the eroding bank was nearly straight in 1955, but since then has developed a radius of curvature of about 2800 feet.

The park has some unique morphology, with floodplain channeling trending parallel to the floodflow direction. These are probably formed by scouring from high-velocity floodflows. Large valley oaks line these flood channels. The area was mapped by Helley and Harwood (1985) as Recent stream channel deposits.

A typical cross-section of the bank is composed of three layers. The top one foot consists of dark gray, somewhat organic silt, underlain by about 20 feet of light brown silt with thin lenses of sandy silt and sand. These two units are floodplain deposits, commonly referred to as the Columbia soil series. Below the flood plain deposits are sand and gravel. These represent older stream channel and point bar deposits from previous meandering episodes. Well completion reports from nearby wells indicate that the sand and gravel continues to depths of 40 to 60 feet. This was the tallest eroding bank measured in the Red Bluff to Colusa reach of the river. Only minor bank recession was measured at this site. Most of this was caused by bank slumping behind the Palisades. Silt and sand deposited between the nets to depths of 3 to 7 feet.

### Foster Island

This site is at River Mile 211.5, on the right bank on the upper part of Foster Island. The site is approximately 9 miles south of Woodson Bridge, as shown on Plate 11. Plate 4 shows that at this site, the river has been slowly moving from the east side of the meander belt downstream to the west. Vegetation alternates between grassland and dense riparian vegetation in about equal amounts. The bank consists of an upper layer of mostly silt with some sand, underlain by mostly

gravel with some sand. The bank is mildly curved, with a radius of curvature of 3,800 feet. Plate 1 shows that the river is eroding sediments mapped as part of the historic meander belt.

The hundred-year meander belt is only 1,500 feet wide at this point, although the historic meander belt is much wider, probably in the order of 12,000 feet. The site has had about 1,000 feet of erosion in the last 100 years.

There was very little bank erosion at this site between June 1988 and November 1992, with a maximum of 4 feet, occurring at stake 11 in the upper third of the site. Average bank erosion between June 1988 and June 1990 is less than one foot. During the winter storms of the 1993 water year, a maximum of 32 feet of bank erosion was recorded on the lower third of the site.

### Big Chico Creek

This erosion site is a bit more than a mile below Big Chico Creek on the east bank, at River Mile 192.5 (Plate 12). It is about two miles above the confluence of the Sacramento River and Stony Creek. Bank erosion was measured here between June 1988 and August 1993. Plate 2 shows that the eroding bank is part of the historic meander belt.

It is mostly a riparian site, with large, mature trees and thick riparian jungle over much of the bank. The site is 3,200 feet long. The bank consists of a thick layer of sandy silt underlain by a sandy gravel. The geologic units are shown on Plate 2.

This is an area where the river has moved more than 3,000 feet in the past 100 years (Plate 5). The river bank has receded about 500 feet since 1969. Riprap occurs upstream of the site. The site has no clearly defined radius of curvature because of irregularities in the bank, but the eroding portion is nearly straight.

The west bank is a gravel bar that has constricted the river near the head of the erosion site. Most of the erosion is occurring in this constricted reach. Between June 1988 and November 1992, maximum erosion occurred at stake 15, with about 67 feet of erosion. During the 1993 water year, a maximum of 25 feet eroded.

### Phelan Island

The Phelan Island site is on the west bank at River Mile 191.7 about one mile above the confluence of the Sacramento River and Stony Creek. Details of the site are shown on Plate 13 and the geology on Plate 2. The bank vegetation is orchard along the entire length. The site was surveyed from August 1986 until June 1988. It was riprapped during the fall of 1988 and the site was discontinued. The radius of curvature is about 2,200 feet. The river has not migrated through Phelan Island in the last 100 years, but geomorphic evidence suggests that the river migrated through the area shortly before that (Plate 5).

### Golden State Island

Golden State Island is at River Mile 190.5 on the east bank about one-half mile north of Stony Creek (Plate 14). The geology is shown on Plate 2. The site was surveyed between August 1986 and June 1988. The site was riprapped in the fall of 1988. Golden State Island is an old meander loop that was cut off in the late 1930s (Plate 5). No information is available on bank composition because the site was riprapped prior to bank sampling. Dense riparian jungle occurs near the top and at the bottom of the site. Grass and an open field occur in the middle.

The 100-year meander belt is about 5,500 feet wide at this point. There is evidence of a wider zone of historic meandering. The river moved about 900 feet eastward into the old meander loop between 1969 and 1988.

The radius of curvature is about 1,900 feet. Rapid erosion was occurring at the site prior to riprapping. The maximum erosion between August 1986 and June 1988 was 53 feet.

Most of the erosion occurred in the middle and lower part of the site.

### Rancho de Farwell

This site is on the west bank at River Mile 186, about 1.5 miles above Ord Ferry Bridge, as shown on Plate 15. The entire site is in orchard. The bank material varies, with sandy silt underlain by sandy gravel in the upper and lower third of the site. The midportion of the site with the majority of the erosion, consists predominantly of an unconsolidated sandy gravel. The radius of curvature is about 2,200 feet and the site is 4,800 feet long. The site was surveyed between August 1986 and August 1993.

The river has not been at this location in the last 100 years (Plate 5), but geomorphic evidence suggests that the river was there shortly before that. The 100-year meander belt is only about 3,000 feet wide at this point. Meander scrolls and arcuate geomorphic features indicate that the historic meander belt is much wider, on the order of 12,000 feet.

Plate 2 shows that the river is presently eroding the historic meander belt along most of the erosion site. Stereo aerial photo pairs confirms that the lower bank is higher in elevation.

This site is highly erodible. A maximum of about 80 feet of erosion occurred toward the middle of the site between August 1986 and November 1992. During the winter of 1992-1993, a maximum of 190 feet of erosion occurred. The maximum combined erosion was 262 feet.

### Ord Ferry

The Ord Ferry site is on the east bank at River Mile 183, about one mile downstream from Ord Ferry Bridge (Plate 16). It is in an area where the river has steadily and consistently eroded the east bank, for a total of about 3,000 feet in the last one hundred years (Plate 5). Riprap extends

down to the site's upstream end. The site has been surveyed between August 1986 and December 1993.

Riparian jungle occurs on the upstream one-half of the eroding bank, with grass on the second half. Much of the upstream bank is underlain by an erosion resistant clay plug, the remnants of an oxbow lake deposit. Helley and Harwood (1985) mapped this deposit as stream channel deposits. Plate 2 shows that older stream channel deposits occur along the upstream end; however there is a thin sliver of historic meander belt deposits along the bank that is too thin to map. Meander belt deposits occur at the lower end. The hydraulic radius is about 2,300 feet. The west bank consists of a large gravel bar with emergent riparian vegetation. The bank receded a maximum of about 34 feet between August 1986 and November 1992. The maximum amount of erosion recorded between November 1992 and December 1993 was 43 feet.

#### Hartley Island # 2

This site is on the right bank at River Mile 173 about 4 miles upstream from Butte City (Plate 17). The site is on the downstream end of the meander around Hartley Island. Bank erosion has been measured here between June 1988 and December 1993. The vegetation consists of, from upstream to downstream, orchard, riparian, cropland, riparian, grass and riparian. The opposite bank on the inside of the bend is mostly gravel bar and young riparian vegetation. The Hydraulic radius is about 2,800 feet.

The bank erosion is occurring in deposits mapped as historic meander belt on Plate 3 and by Helley and Harwood (1985) as stream channel deposits. The upstream part of the eroding bank is in the historic meander belt but not in the 100-year meander belt (Plate 6). The downstream part has been eroded at various times as the river migrated from west to east.

A maximum of about 11 feet of erosion occurred at this site between June 1988 and November 1992. Between November 1992 and December 1993 the maximum amount of erosion was 27 feet.

#### Hartley Island # 1

Hartley Island # 1 is at River Mile 172.5 on the east bank about 3.5 miles upstream from Butte City (Plate 18). The eroding site is in a walnut orchard with some riparian toward the middle of the site. Bank composition has not been mapped at this site. The site has been surveyed from August 1986 to August 1993.

The river has migrated steadily eastward a distance of about 2,500 feet for the last 100 years and the meander belt is 3,500 feet wide (Plate 6). The point bar developing on the inside of the bend is mostly young riparian vegetation. The hydraulic radius is about 2,200 feet.

The bank erosion is occurring on historic meander belt deposits (Plate 3). These deposits are over 100 years old.

Most of the erosion appears to occur at the downstream end of the bend. Maximum erosion is about 112 feet, with 52 feet occurring between November 1992 and August 1993.

#### Larkins Island

Larkins is at River Mile 171.0 on the west bank about 2.5 miles above Butte City (Plate 19). The site has been surveyed since 1986 to the present. The river has been slowly migrating westward through the historic meander belt (Plate 3). Bank vegetation is entirely orchard. Bank composition has not been mapped at this site.

The 100-year meander belt is only about 2200 feet wide in this area and the river has eroded westward about 1,000 feet during this time (Plate 6). The vegetation is mostly field crops at the upstream end and orchards in the lower end. The hydraulic radius of the eroding bank is 2,000 feet. The opposite bank is a gravel point bar with incipient riparian vegetation.

Most of the erosion during the 1986-1992 drought occurred in the midportion of the bend. A maximum of 24 feet of bank recession occurred between July 1986 and November 1992. During the winter of 1992-1993, a maximum 54 feet of recession occurred on the downstream end of the meander bend.

#### Packer Island

This site is on the right bank at River Mile 167.0 (Plate 20). It has been surveyed since June 1988. The site has a wide variety of vegetation, including riparian, grassland and orchards in patches. The river is eroding westward, about 2,000 feet since 1896 (Plate 6). The meander belt is about 4,000 feet wide at this point. The hydraulic radius is about 2,000 feet. The east bank is mostly an open gravel bar with a band of riparian vegetation along a recent river cutoff. A maximum of about 142 feet were eroded during the survey period, of which 120 feet eroded between November of 1992 and August 1993. Most of the erosion occurred on the downstream end of the bend. Plate 3 shows that the river is eroding the historic meander belt.

#### Princeton

The Princeton site is on the southeast bank at River Mile 164.7, about one mile upstream of the town of Princeton, as shown on Plate 21. The site was monitored between August 1986 and August 1993. This site was also monitored between 1977 and 1979 (DWR, 1979). The site is the most erodible site measured, and at present probably also the most erodible bank on the Sacramento River. The meander belt is about 3,500 feet wide (Plate 6). Contrary to most banks, the Princeton site is eroding laterally southward, and is not showing typical meander development. The river has moved in this direction more than 3000 feet since 1896, and as much as 2,200 feet since 1935.

The river is eroding a meander loop that was cut off prior to 1896 (Plate 3). The banks consist of a thick layer of unconsolidated silt underlain by medium to fine gravel. According to Helley and Harwood (1985), the eroded deposit is Quaternary Alluvium. The bank vegetation is prune orchard. Several buildings and an equipment yard have been lost in the last five years. The northwest bank is low terrace riparian vegetation. The eroding bank is scalloped but fairly straight. No definable radius of curvature can be assigned to this bank. A maximum of about 150 feet of bank recession occurred between August 1986 and November 1992. In the winter of 1992-1993, a maximum 150 feet of erosion occurred.

### Jimeno Rancho

Jimeno Rancho erosion site is at River Mile 156.5 on the west bank (Plate 22). The site is about 2 river miles south of Moulton Weir. This site has been surveyed between June 1988 and August 1993. Orchards occur on the overbank area. The radius of curvature is about 1,600 feet. A point bar with gravel and riparian vegetation has developed on the east bank.

The meander belt is narrow, less than 2,000 feet (Plate 6). The river is eroding historic meander belt material (Plate 3) deposited more than 100 years ago, mapped as stream channel deposits by Helley and Harwood (1985). A maximum of 44 feet eroded during the monitoring period.

### Results

Table 8 shows the results from the sixteen erosion sites.

A number of other variables other than duration and magnitude of discharge affect bank erosion rates. Some of those suggested include the resistance to entrainment by the bank materials (bank composition), radius of curvature of the bend, bed material sediment transport capacity of the flows, bank height, and degree of root reinforcement of the bank by vegetation.

Our bank erosion study began in 1986, at the same time as California's extended seven year drought. Most of the data gathered were from low-flow erosion. High flows occurred in the winter and spring of 1993. These data are included in the report, but detailed analysis were not done in time for this report.

Bank composition has been identified as one of the factors influencing bank erodibility.

Our preliminary results indicate a significant positive correlation between the amount of bank erosion and discharge. It was noted that more erosion occurred during discharge events above base flow than at base flow alone. The amount of erosion attributable to these peak events will be quantified by subtracting base flow erosion (low flow) from peak event erosion (high flow) and developing discharge vs. erosion relations. Base-flow erosion from May through November 1987 averaged 1.0 feet per site with values ranging from a low of 0 feet erosion at Toomes Creek to a high of 3.8 feet at Princeton erosion site. This corresponded to an average base flow of 8,370 cubic feet per second over 180 days. Erosion from December 9, 1986 through May 18,

1987 ranged from a low of 0 feet at Toomes erosion site to a high of 12.6 feet at Princeton. This corresponded to an average flow of 19,020 cfs during 54 days when discharge exceeded base flow during this 157-day period. Erosion from November 21, 1987 through June 7, 1988 averaged 5.1 feet per site from a low of 0 feet at Toomes Creek erosion site to a high of 18.9 feet at Princeton. This corresponded to an average flow of 18,180 cfs during 58 days when discharge exceeded base flow during this 196-day period.

Princeton and Golden State Island erosion sites had the most active erosion, averaging 15.1 feet during the two high-flow periods and 2.5 feet during the one base-flow period.

There is the possibility that survey benchmarks may be lost during flooding.

Golden State Island and Phelan Island were ripped by the Corps of Engineers and have therefore been dropped from DWR's erosion monitoring project. However, it may prove useful to continue monitoring these locations in other ways. Some of the first surveys were done using angles that were not repeated in later surveys. It was found that the resulting data could not be used for comparative purposes. Consequently, the most recent erosion surveys also included these old angles in order to use the initial surveys.



**TABLE 8 SACRAMENTO RIVER BANK EROSION SITES**

Site Name	Years Surveyed	Maximum Erosion (Feet)	Mean Erosion (Feet)	Eroded Silt (Yard <sup>3</sup> )	Eroded Gravel (Yard <sup>3</sup> )	Average Eroding Bank Length (Feet)
Coyote Creek	1988-93	19	11	14310	18310	2960
Toornes Creek I	1986-93	9	5.2	8000	1310	1650
Toornes Creek II	1986-92	37	18	42660	9990	3100
Palisades 1	1986-89	10	3.4	29770	5430	2640
Palisades 2 <sup>^</sup>	1990-91	1.2	1.2	3150	570	2690
Palisades 3 <sup>^</sup>	1991-92	1.4	0.7	1940	350	2710
Foster Island	1988-93	32	12	39970	15250	5260
Big Chico Creek	1988-93	77	41	89510	41350	3490
Phelan Island 1	1986-87	2.6	1.2	*	*	3930
Phelan Island 2 <sup>^</sup>	1987-88	3.8	0.9	*	*	3970
Golden State Island	1986-88	53	29	*	*	3200
Rancho de Farwell	1986-93	262	128	297540	256560	5000
Ord Ferry	1986-92	34	23	*	*	3620
Hartley Island II	1988-92	11	3.9	*	*	5510
Hartley Island I	1986-93	112	54	*	*	5660
Larkins Island	1986-93	54	26	*	*	4340
Packer Island	1988-93	142	69	*	*	4150
Princeton 1	1986-91	140	103	*	*	2070
Princeton 2 <sup>^</sup>	1991-93	182	89	*	*	3040
Jimeno Rancho	1988-92	44	35	*	*	3740

<sup>^</sup> Same erosion site but different survey backsights

\* Silt and gravel volumes not available

## **FLOODPLAIN DEPOSITION**

Floodplain deposition regenerates high-terrace soils lost by bank erosion. Bank erosion occurs year-round. The floodplain deposition occurs during large floods on an episodic basis. An average of 3 to 6 inches to, in places, several feet of silt may be deposited during a single flood. The deposition process can rebuild high-terrace soils at a fairly rapid rate. Areas that were river bottom in the 1940s are presently being farmed. The rate of formation of high terrace soils has been reduced by flood control.

It was believed (USCE 1978) that through bank erosion, high-terrace lands were being replaced by low-terrace point bars because Shasta Dam reduced deposition of soils on the floodplain. Observations made during this study indicate that this may not be the case. After the flood of March 1983 and February 1986, floodplain deposition was observed in a number of places. Deposition varied from zero inches to over 2 feet, with an average of several (3-6) inches within the flooded area. Although the incidence of floodplain deposition has decreased, so has the rate of bank erosion. In a study of land use changes in the Sacramento River Riparian Zone, DWR (1983) came to a similar conclusion:

"....there has been no overall loss of high-terrace prime soils from 1946 through 1982. Erosional losses of soil, both in orchard and riparian vegetation, have been severe, but natural soil building processes have created an equal or slightly greater amount of prime high-terrace soil."

It is not known if the present high terrace soils are at a lower elevation than pre-Shasta Dam high terrace soils.

### **Floodplain Cross-Sections**

Five cross-sections were surveyed during the summer of 1986. These extend from one side of the floodplain or centerline of a project levee, across the floodplain, across the Sacramento River to the opposing side of the floodplain or project levee. These surveys re-established historic profiles done by the U. S. Geological Survey during the mid-1970s. Cross-sections were located at the Glenn-Colusa Irrigation Canal, Pine Creek, Jacinto, Butte City and Moulton Weir. Elevations were run at intervals of 20.0 feet and read to tenths of a foot. All level loops were closed and checked.

In the summer of 1988, five additional cross-sections were surveyed. These include cross-sections at the Red Bluff Diversion Dam, Sacramento Bar, Tehama-Los Molinos, Woodson Bridge and Hamilton City. These cross-sections are compared to U.S. Army Corps of Engineers cross-sections surveyed between 1917 and 1923. The locations of the ten floodplain cross-sections are shown on Figure 20 and summarized on Table 9.

**TABLE 9 SURVEYED FLOODPLAIN CROSS-SECTIONS**

SURVEYED CROSS-SECTION	RIVER MILE	YEARS SURVEYED	
Red Bluff Diversion Dam	243.0	1917	1988
Sacramento Bar	235.6	1923	1988
Tehama-Los Molinos	227.5	1923	1988
Woodson Bridge	218.4	1917	1988
Hamilton City	206.0	1917	1988
Glenn-Colusa Irrigation Canal	201.2	1977	1986
Pine Creek	197.7	1980	1986
Jacinto	175.4	1972	1986
Butte City	168.5	1979	1986
Moulton Weir	158.7	1976	1986

Red Bluff Diversion Dam - River Mile 243.0

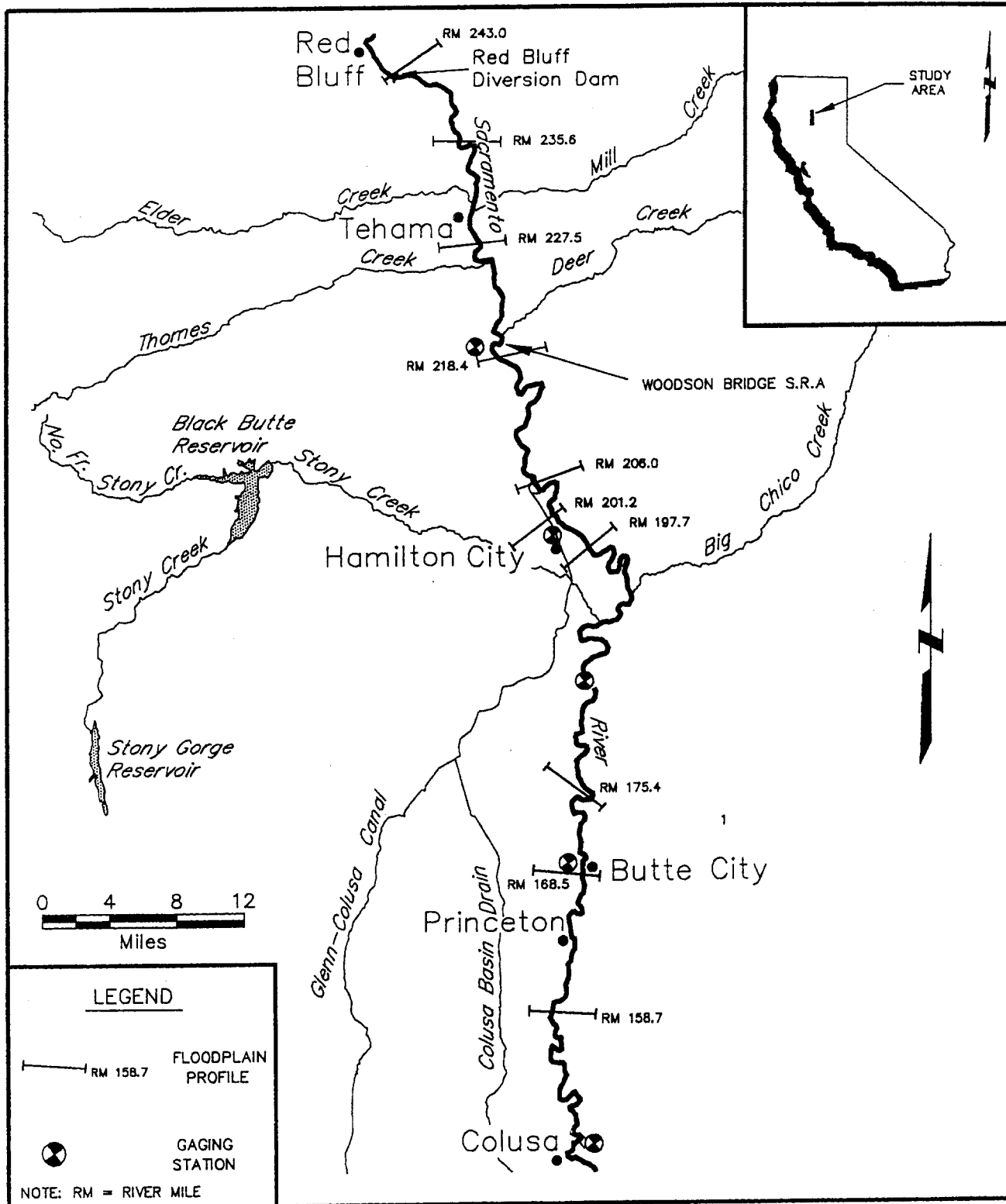
This cross-section was originally surveyed by the U.S. Corps of Engineers in 1917. The River Mile 243.0 cross-section is at the Red Bluff Diversion Dam (Figure 21). The cross-section crosses the dam axis and traverses across open and tilled fields. Elevations are only shown on the east bank of the river. The section showing elevations is about 8,600 feet long. Survey monuments were established in the parking lot of the diversion dam and near the right abutment. Maximum silt deposition in floodplain swales is 15 feet. The river moved about 500 feet eastward between the two surveys.

Elevations were taken from a U.S. Geological Survey monument on the east abutment of the diversion dam.

Sacramento Bar - River Mile 235.6

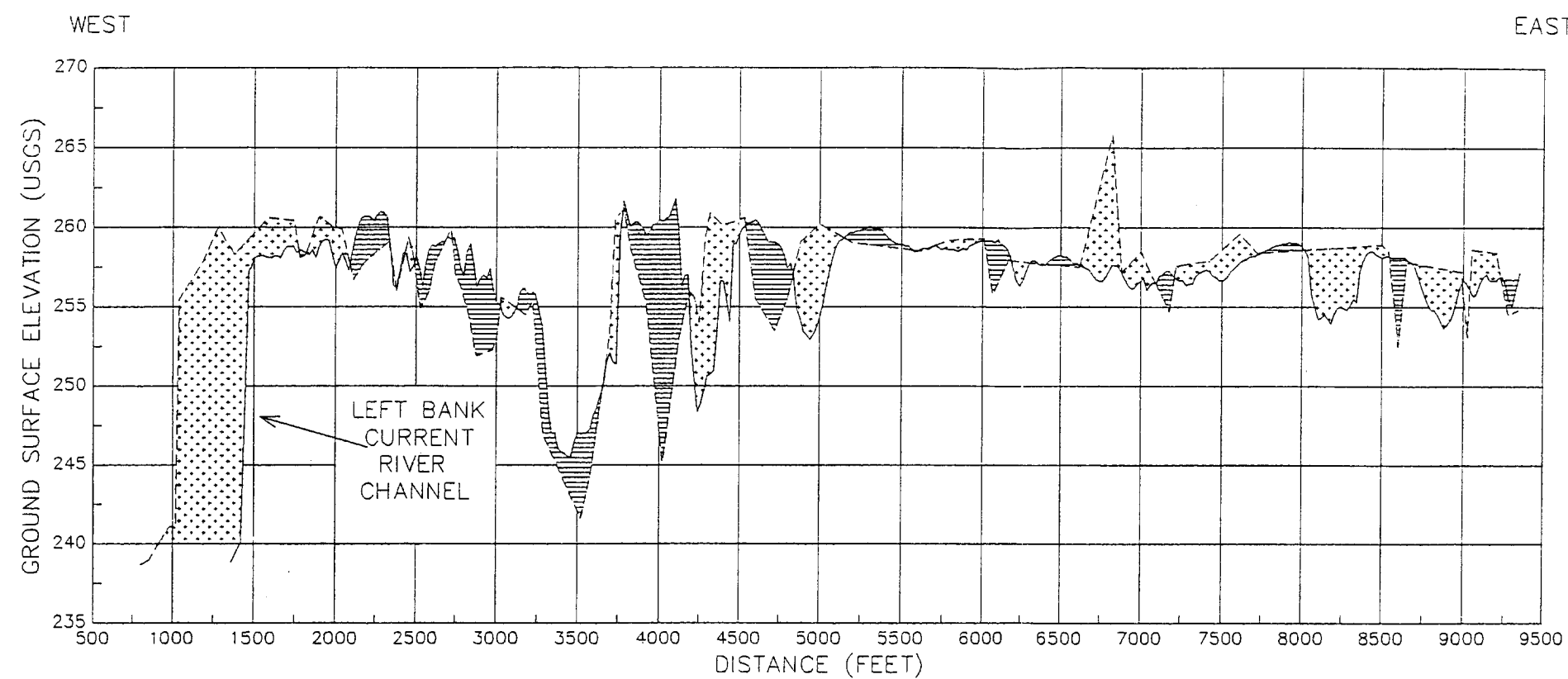
The River Mile 235.6 cross-section crosses Sacramento Bar, about 9.5 miles south of Red Bluff (Figure 22). The cross-section begins on the east side near the intersection of Antelope Creek and Clement Avenue and extends about 6,600 feet across the floodplain to the levee on the west side of the Sacramento River. Comparison of the 1988 and the 1923 cross-sections shows that the river has moved about 2,500 feet southeast by meander cutoff, and the old channel has been filled in by an average of about 20 and a maximum of 26 feet of sediment.

Figure 20



STATE OF CALIFORNIA  
THE RESOURCES AGENCY  
DEPARTMENT OF WATER RESOURCES  
NORTHERN DISTRICT

# Sacramento River Bank Erosion Investigation Floodplain Profile Locations Sacramento River from Red Bluff to Colusa

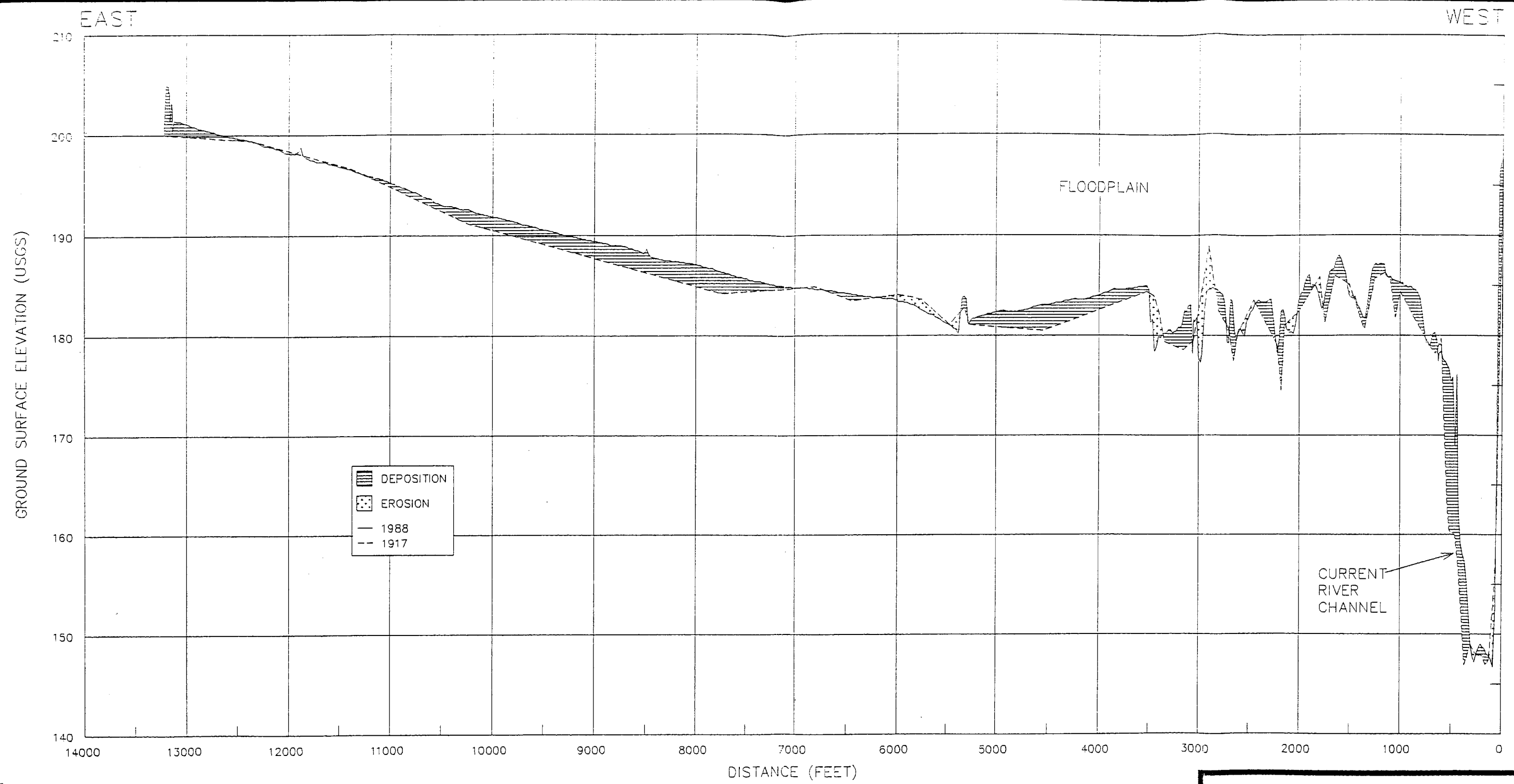


STATE OF CALIFORNIA  
THE RESOURCES AGENCY  
DEPARTMENT OF WATER RESOURCES  
NORTHERN DISTRICT

Sacramento River  
Bank Erosion Investigation

Changes in Floodplain Cross Section

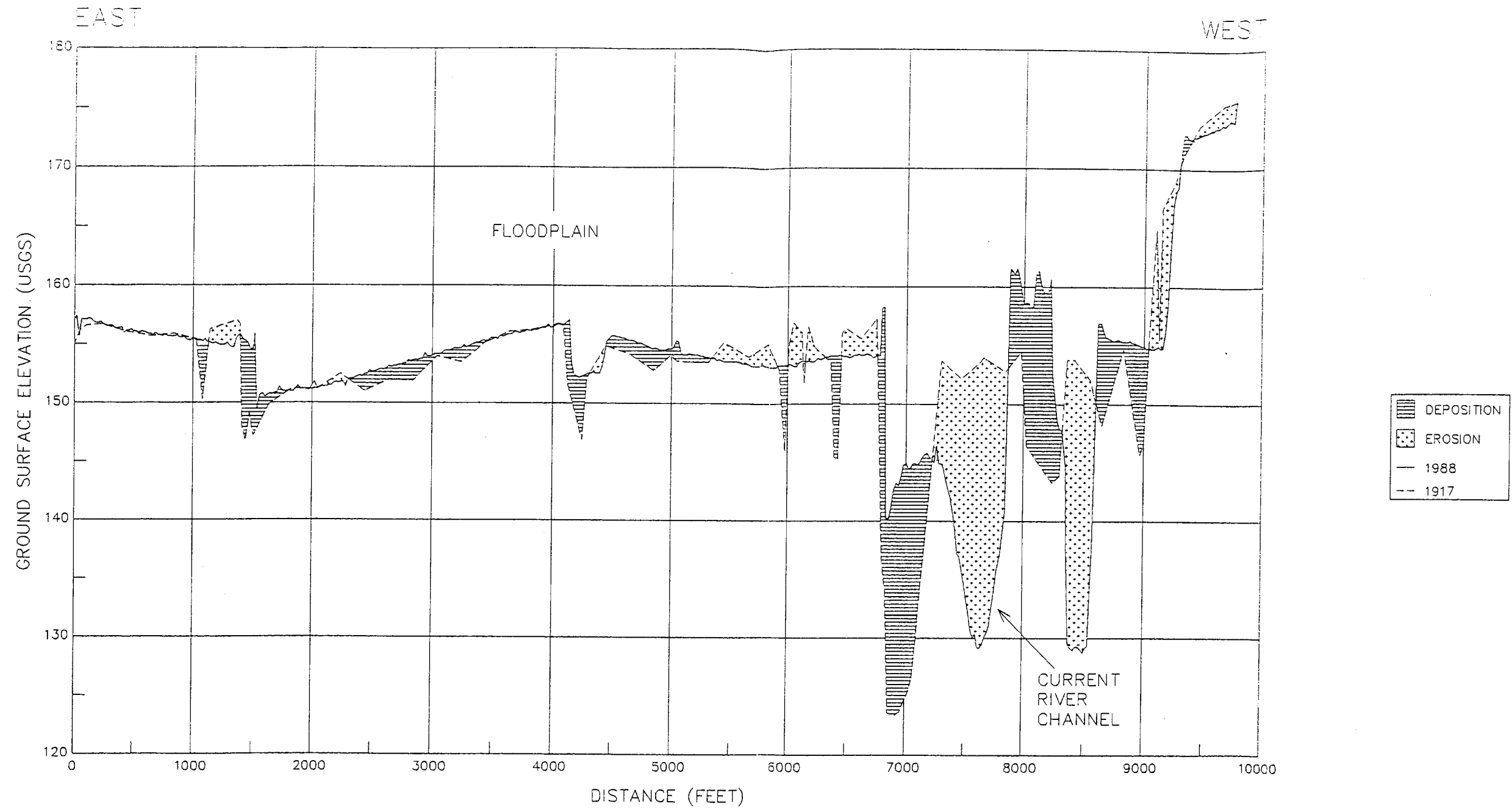
River Mile 243.0



STATE OF CALIFORNIA  
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NORTHERN DISTRICT

Sacramento River  
Bank Erosion Investigation

Changes in Floodplain Cross-Section  
River Mile 218.4



STATE OF CALIFORNIA  
 THE RESOURCES AGENCY  
 DEPARTMENT OF WATER RESOURCES  
 NORTHERN DISTRICT

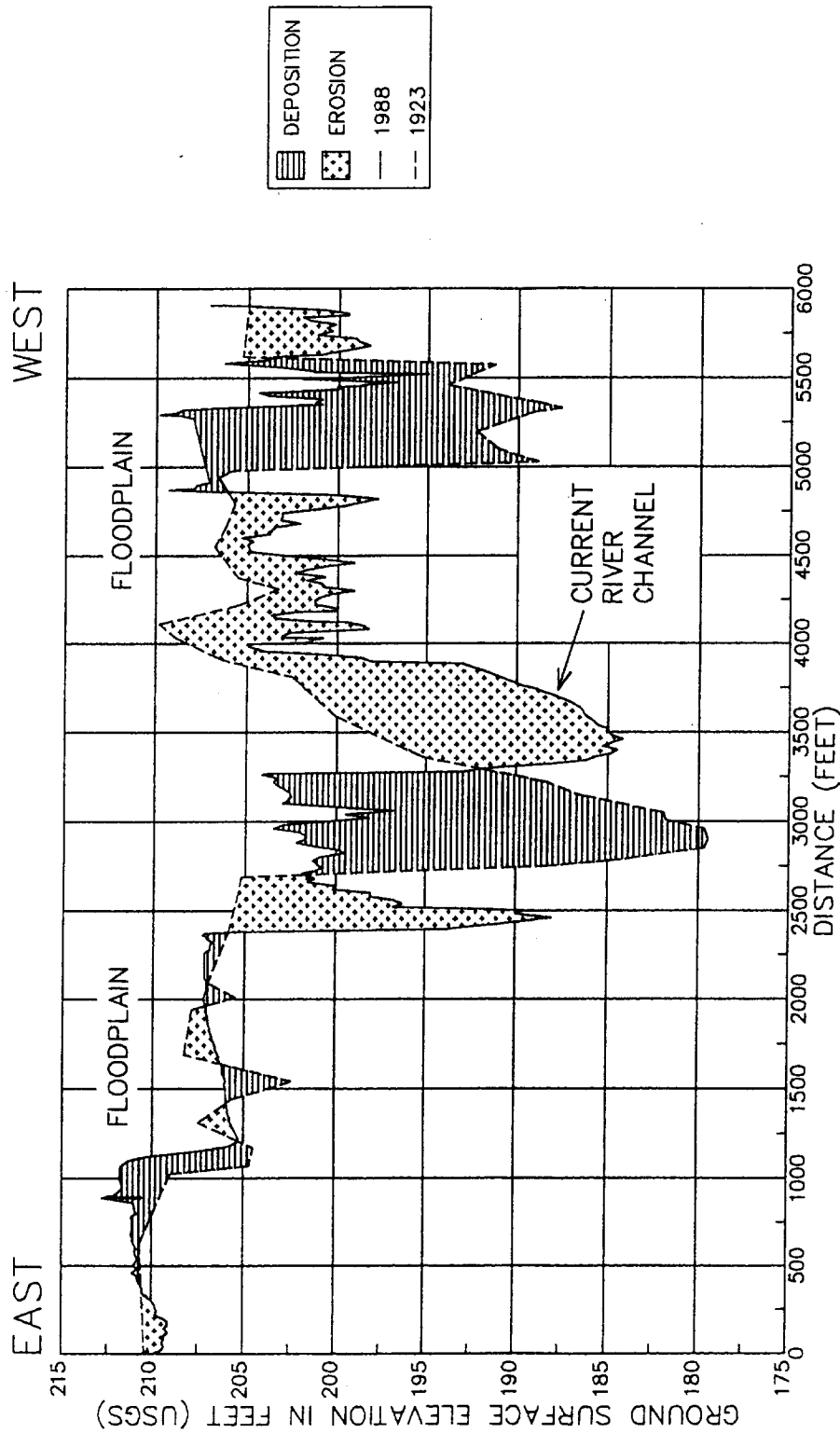
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Sacramento River  
 Bank Erosion Investigation

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Changes in Floodplain Cross-Section  
 River Mile 206.0

Figure 23



Sacramento River  
Bank Erosion Investigation

Changes in Floodplain Cross-Section at River Mile 227.5



USGS elevations were brought in from the west side of the pumps. Comparing the 1986 cross-section to the 1917 shows that the river has moved about 600 feet west and deposition has occurred behind it. It also shows a second channel on the west side that serves as the inlet to the pumps. This channel is maintained by dredging and depositing the material on the island between the two channels. Overbank deposition also appears to be occurring on the east side floodplain. Some of this may be due to leveling and infilling prior to orchard planting.

About 20 feet of deposition has occurred in the 1917 channel and about 23 feet of erosion has occurred in the location of the 1988 channel. The thalweg of the 1917 channel is about 7 feet lower than the 1988 channel.

#### Glenn-Colusa Irrigation Canal - River Mile 201.2

The section at River Mile 201.2 is only about 2,000 feet long (Figure 26). It extends from a riprapped levee road on the eastern river bank, across the river, through an orchard to the levee on the west bank. The cross-section was first surveyed by the USGS in 1977 and resurveyed by DWR in the summer of 1986. A considerable amount of channel erosion appears to have occurred during that period. The east bank is stable because of the riprap and no lateral erosion has occurred. This cross-section has degraded overall by 0.68 feet mostly because of the channel erosion, but the floodplain appears to have neither aggraded or degraded substantially.

#### Pine Creek - River Mile 197.7

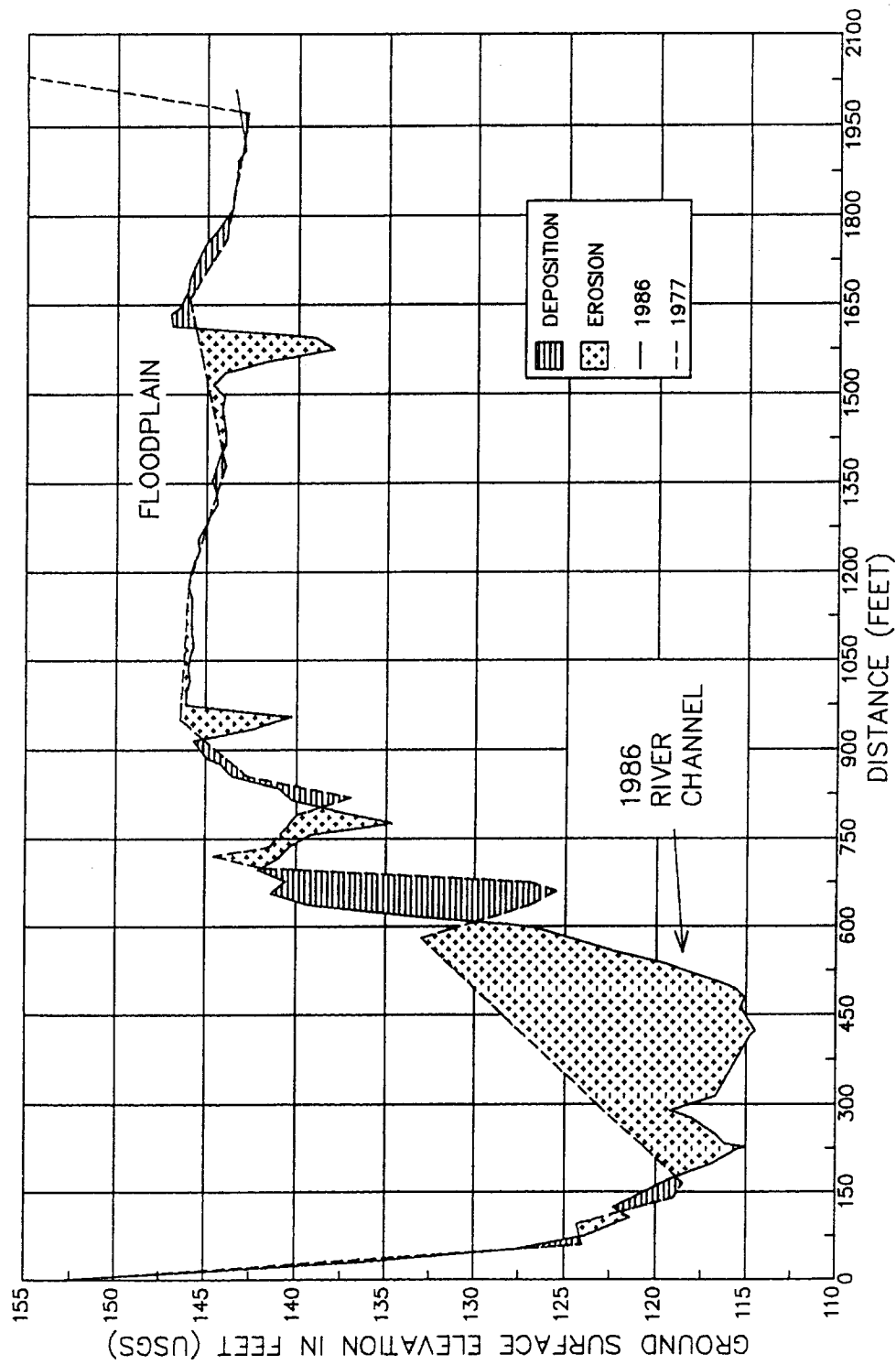
This cross-section is about one and a half miles below the Hamilton City Bridge (Figure 27). It extends from an elevated levee road on the west side, through some orchards to the riprapped bank of the Sacramento River. The east side consists mostly of riparian vegetation with alternating strips of trees and grass. The cross-section terminates on a levee road. Total distance is about 4,500 feet.

The channel section appears to be stable because of the riprapped bank. The maximum depth increased about 2 feet during this time period. Both deposition and erosion occurred on the east side and deposition on the west side. Overall, the profile lost 0.3 feet between 1980 and 1986, although the floodplain had net deposition.

#### Jacinto - River Mile 175.4

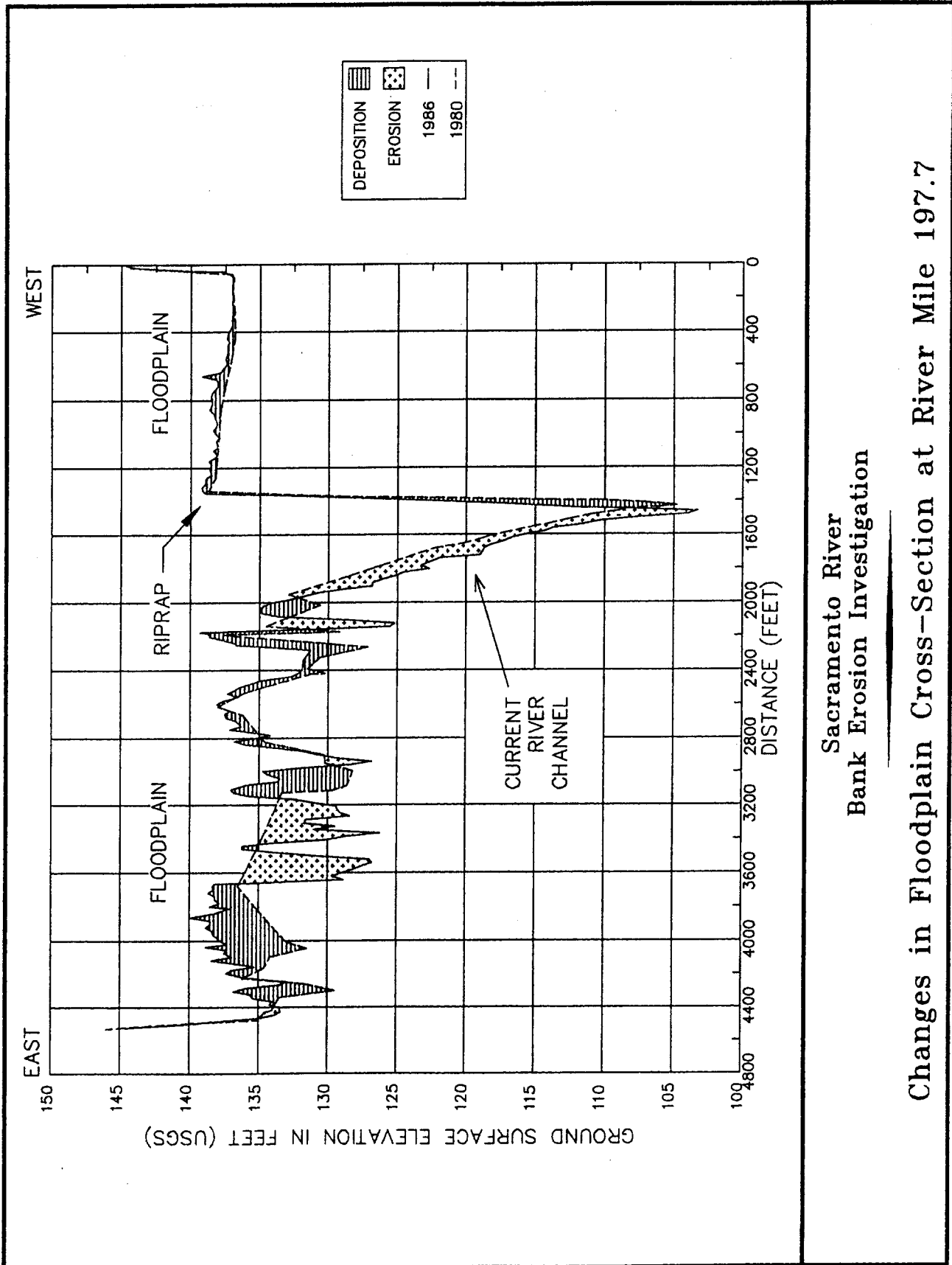
River Mile 175.4 cross-section is directly north of Hartley Island, a few miles north of the town of Glenn (Figure 28). Only the channel section was surveyed in 1988, but the old section extends from the project levee on the west side, across the Sacramento River onto a meander loop cutoff, across a slough and an orchard to the project levee on the east side.

Figure 26



Sacramento River  
Bank Erosion Investigation  
Changes in Floodplain Cross Section - River Mile 201.2

Figure 27



### Butte City - River Mile 168.5

Cross-section 168.5 is a few hundred feet above the Butte City Bridge and follows parallel to State Highway 162 for a distance of about 4,600 feet (Figure 29). The east side of the cross-section begins on the levee, crosses a river terrace, and intersects the riprapped bank of the Sacramento River. The west side has 3,800 feet of orchards before crossing Razor Slough and minor riparian vegetation. The 1979 section was surveyed by the U.S. Geological Survey and resurveyed by DWR in 1986.

The river has not been eroding in this area in the last 100 years. The east bank is stable because of geologic control and riprap. There is abundant evidence that the river had previously meandered all the way to the western end of the cross-section, at Razor slough. As much as 4 feet of silt was deposited on the west side floodplain between the time of the two cross-sections. The thickness decreased away from the river, until at about 2,800 feet, where some erosion occurred. A maximum of 6 feet was also deposited in Razor Slough. A maximum of about 20 feet of erosion also occurred in the channel, and the thalweg lowered about 14 feet. This channel section is the deepest of the ten cross-sections surveyed. Overall, an average of 0.3 feet of aggradation occurred between 1979 and 1986.

### Moulton Weir - River Mile 158.7

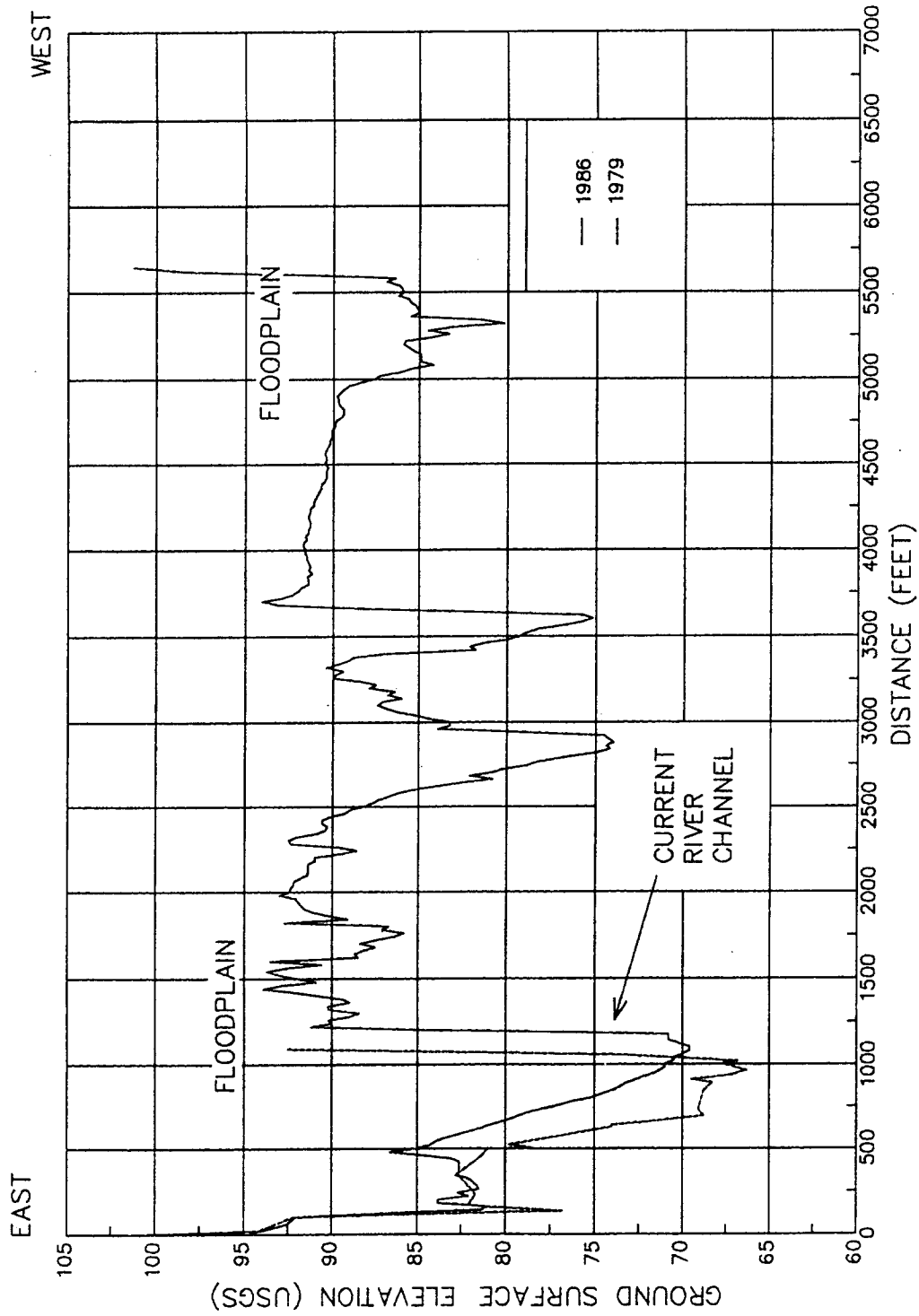
This cross-section is short, only about 2,100 feet long. It is about 1,000 feet upstream of Moulton Weir (Figure 30). The cross-section begins on the project levee on State Highway 45. It traverses a short section of riparian vegetation, then crosses the river, open grassland and some more riparian. The river has actively meandered over the entire cross-section in the last 100 years.

According to the cross-section, about 300 feet of bank recession has occurred on the west bank in the 10 years between the two surveys. During the same time, maximum depth also increased about 10 feet. Deposition occurred in the Riparian forest to the west and on the gravel bar and riparian to the east. Near the river, as much as 15 feet of sediment deposited on the gravel bar.

## **Results**

By comparing the various cross-sections it is clear that the amount of deposition is related to the elevation. Older stream channels and oxbows close to the river will fill relatively fast, with 25 feet of deposition in 70 years, while the stable floodplain far from the river will only deposit or erode a few feet during the same time period. Floodplain erosion also occurs. This happens mostly in areas with narrow floodplains or where the river channel is more stable. Table 10 summarizes the data for the floodplain cross-sections.

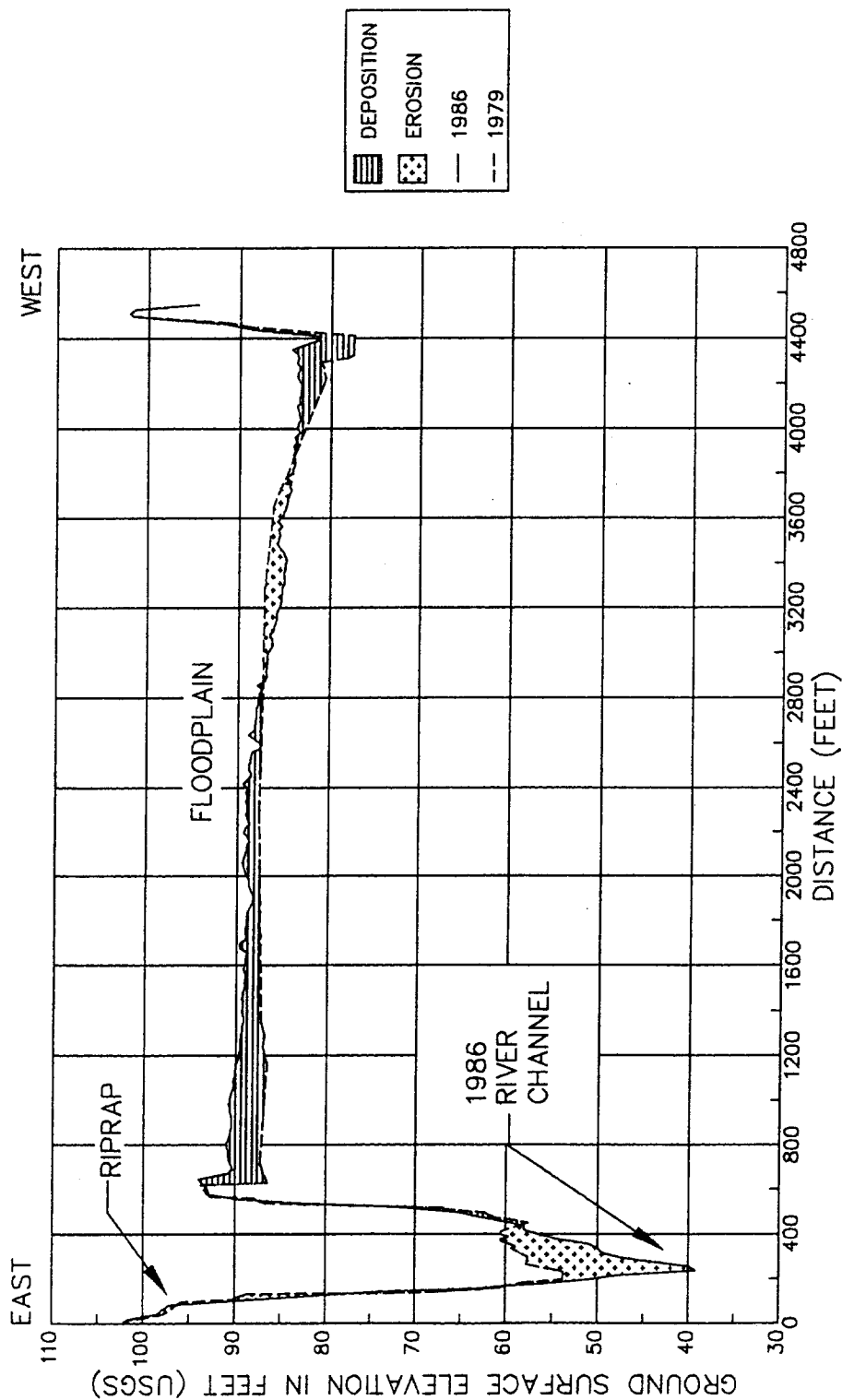
Figure 28



Sacramento River  
Bank Erosion Investigation

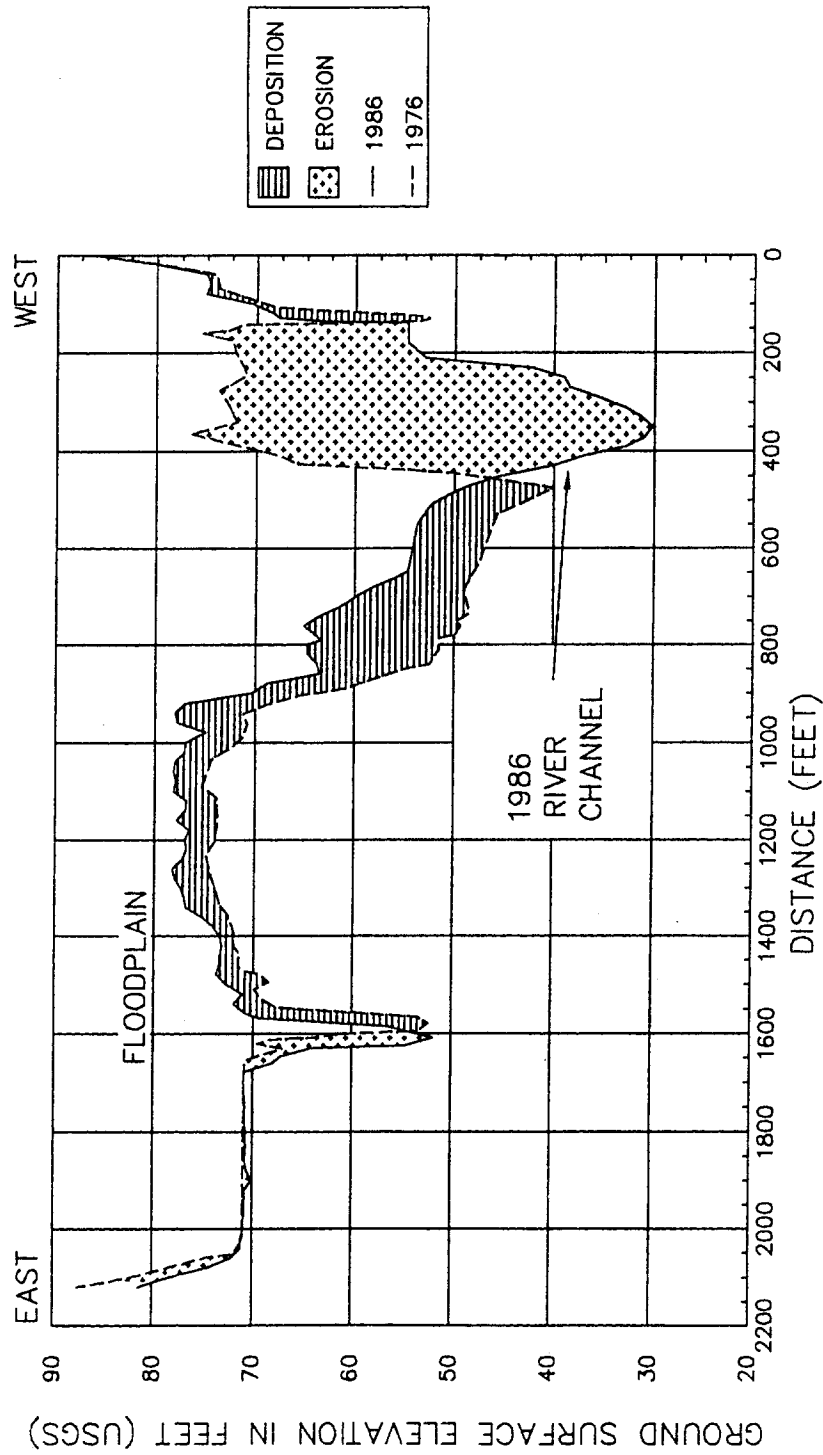
Changes in Floodplain Cross-Section at River Mile 175.4

Figure 29



Sacramento River  
Bank Erosion Investigation  
Changes in Floodplain Cross-Section at River Mile 168.5

Figure 30



Sacramento River  
Bank Erosion Investigation

Changes in Floodplain Cross-Section at River Mile 158.7

**TABLE 10 FLOODPLAIN CROSS-SECTIONS  
CHANGES IN ELEVATION IN FEET**

[illegible]



## LAKE RED BLUFF DEPOSITION

The Red Bluff Diversion Dam is on the Sacramento River immediately below the mouth of Red Bank Creek (Figure 31). The dam was completed in 1966 and is operated by the U.S. Bureau of Reclamation.

Releases to the river are controlled by eleven 60- by 18-foot regulating gates. One of these is the sluice gate located at the right end of the spillway. This gate is provided with automatic controls to aid in maintaining a constant water surface elevation and to sluice sediment from in front of the canal headworks.

The dam maintains Lake Red Bluff at a normal pool elevation of 252.5 feet during the summer and 251.5 during the winter, except when flows exceed 50,000 cubic feet per second and rising. At that point the gates are lifted over a period of two hours until the gates clear the water. The gates are slowly lowered when flows are 50,000 cubic feet per second and declining. Beginning in 1986, the gates were open between October and March to improve fish passage. Backwater effects occur at flows less than 50,000 cubic feet per second. Minor effects from the diversion dam's gate supports occur above this flow.

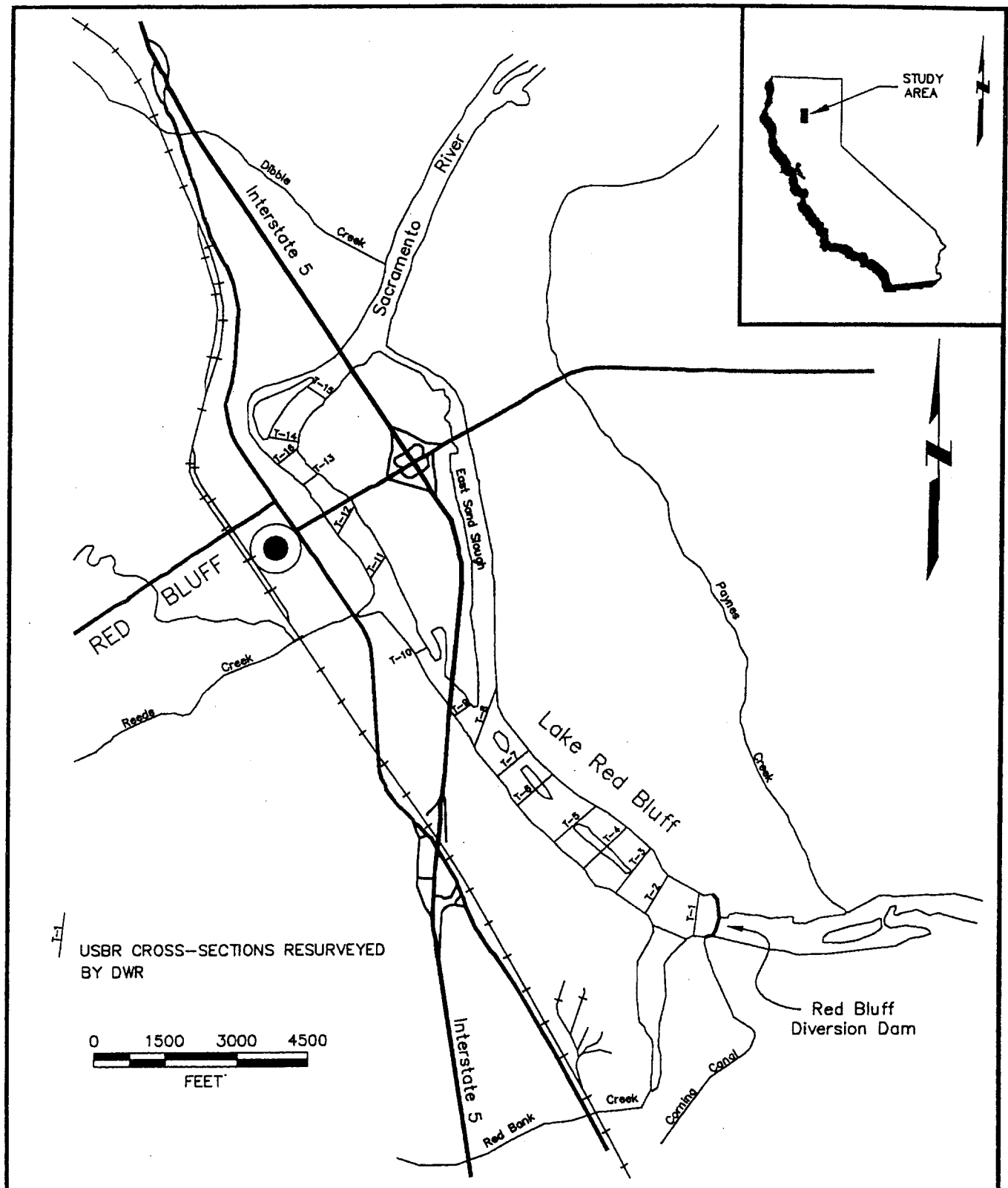
The U.S. Bureau of Reclamation surveyed cross-sections across Lake Red Bluff in 1951, 1962, and 1968 and computed water surface elevations for various flows. They also computed sediment deposition in Lake Red Bluff between December 1966 and February 1968 as 3,600 tons, assuming that all sediment in suspension was sluiced through the dam.

DWR performed sonar surveys at 16 of the original USBR cross-sections of Lake Red Bluff. These were done in 1982, 1986, and 1988 to quantify the backwater effects on sediment deposition during high flow. Aggradation and degradation in the lake is an indicator of the amount of sediment transport in the Sacramento River.

The goals of this program are to examine the backwater effects on in-channel sedimentation and determine the amount of bedload moving down the Sacramento River. Thirty-two monuments were set to mark the ends of the cross-sections in the fall of 1986. These are shown in Figure 31. These monuments are composed of galvanized pipe set in concrete. The distance between monuments was measured using an electronic distance measuring device. The profiles were established by using a paper-feed, depth sounder mounted on a boat. The collected data are plotted to calculate changes in cross-sectional area of the channel at each profile location.

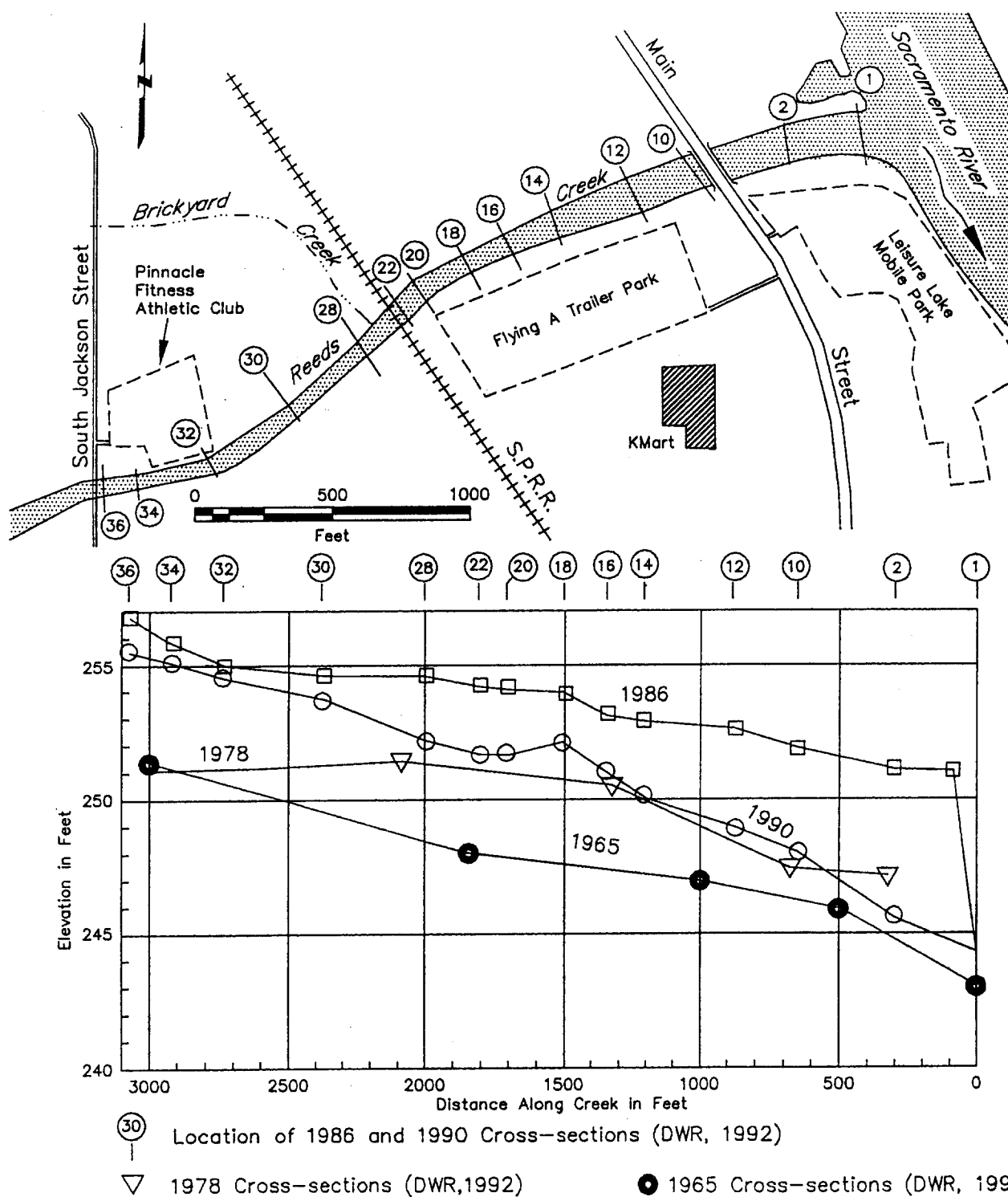
## Changes in the Diversion Dam Operation

The effect of the changes in operation of the Red Bluff Diversion Dam on aggradation on Reeds Creek was investigated as part of the *Sacramento Valley Westside Tributary Watersheds Erosion Study--Reeds Creek Watershed* (DWR, 1991). Figure 32 shows the



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# Sacramento River Bank Erosion Investigation Cross-Section Profile Locations Red Bluff Diversion Dam



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# Sacramento River Bank Erosion Investigation Changes in the Stream Profile Reeds Creek

profile of the lower 3,200 feet of the Reeds Creek channel. About 4 feet of aggradation is evident between the completion of the dam in 1966 and 1986, for a total of about 56,000 cubic yards of sediment. Major stormflows in March 1983 and February 1986 contributed the majority of this sediment. The U.S. Bureau of Reclamation dredged the mouth of Reeds Creek several times to remove accumulated sediment. Since the fall of 1986, the dam has been opened during the winter months and the accumulated sediments are beginning to scour out of the reach.

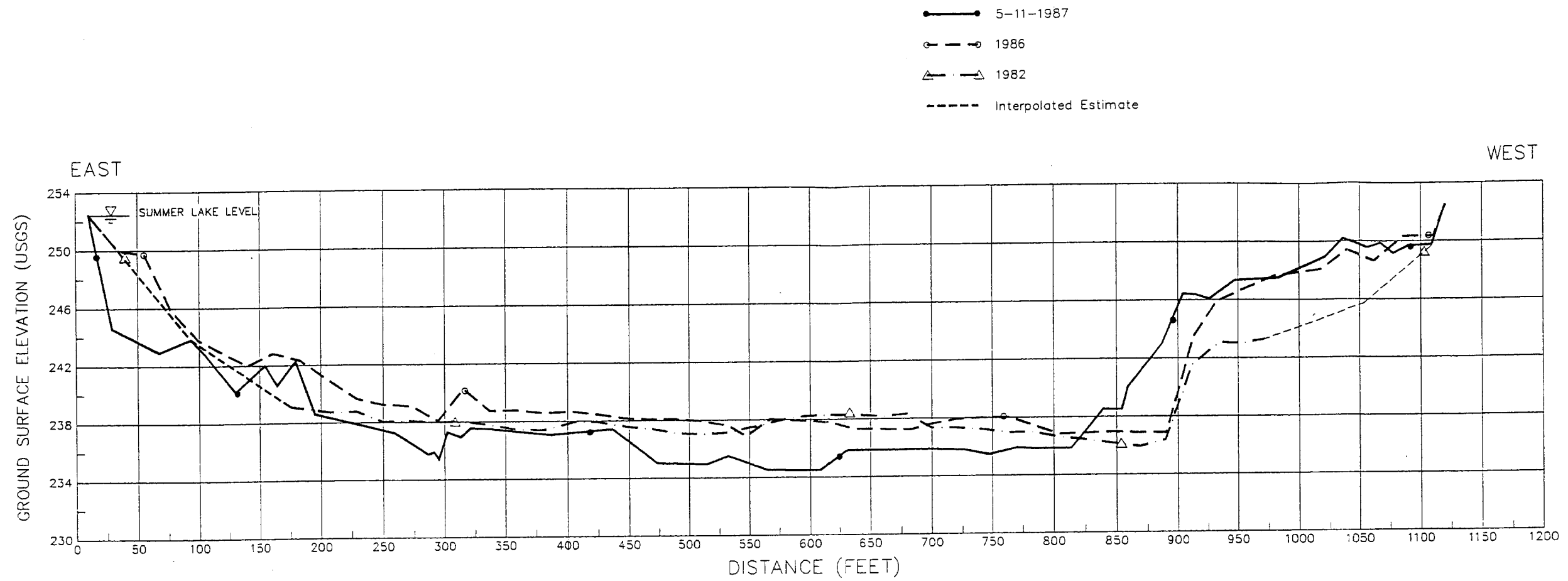
In March 1990, DWR (1991) re-surveyed Reeds Creek, as also shown on Figure 32. The profiles show that, since the dam began opening its gates during the winter runoff, about 35,000 cubic yards of gravel has been flushed out of this section. It would be expected that similar results are occurring on the Sacramento River.

### **Lake Cross-Sections**

The name of each section and the survey dates are shown in Table 11. The cross-sections are shown in Figures 33 to 48.

The U.S. Bureau of Reclamation has reported a continuing problem with concrete erosion above and below the crest of the spillway. The abrasive action of sand and gravel passing over the crest at flood stage is thought to be the cause of this erosion (USBR, 1970).

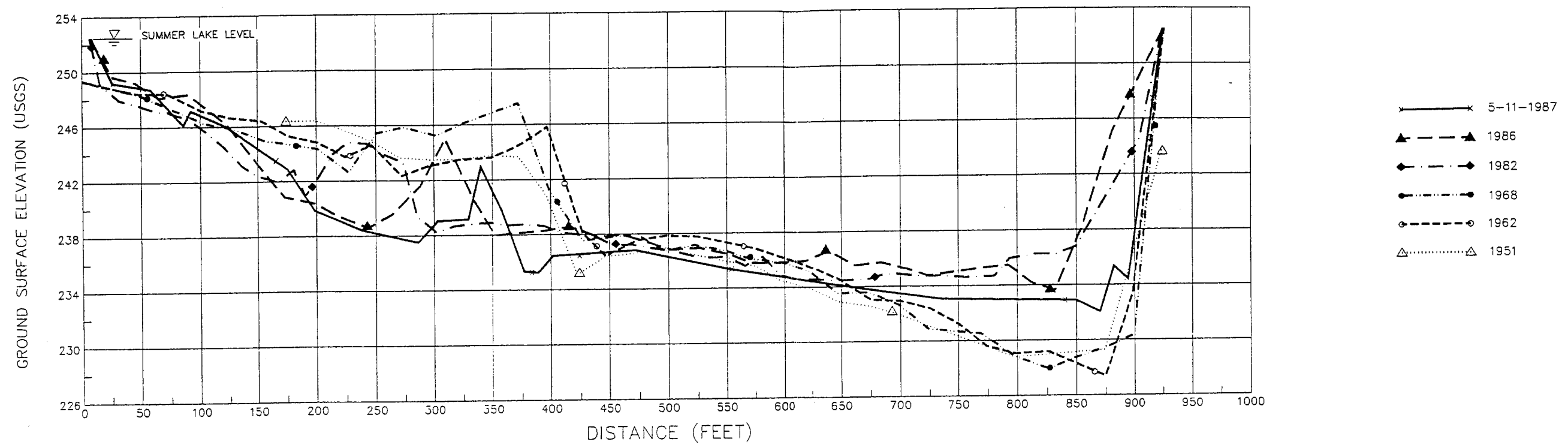
Calculations by the Bureau suggest low bedload sediment transport and low rates of deposition in the reservoir area. Table 12 shows the change in the average depth with time of the different cross-sections. In general, there was aggradation between 1968 and 1986. Between 1986 and 1987, there was degradation. This was the first year that the gates were left open during the winter months. Clearly a new survey should be done to see how effective this is in keeping the reservoir sediment-free.



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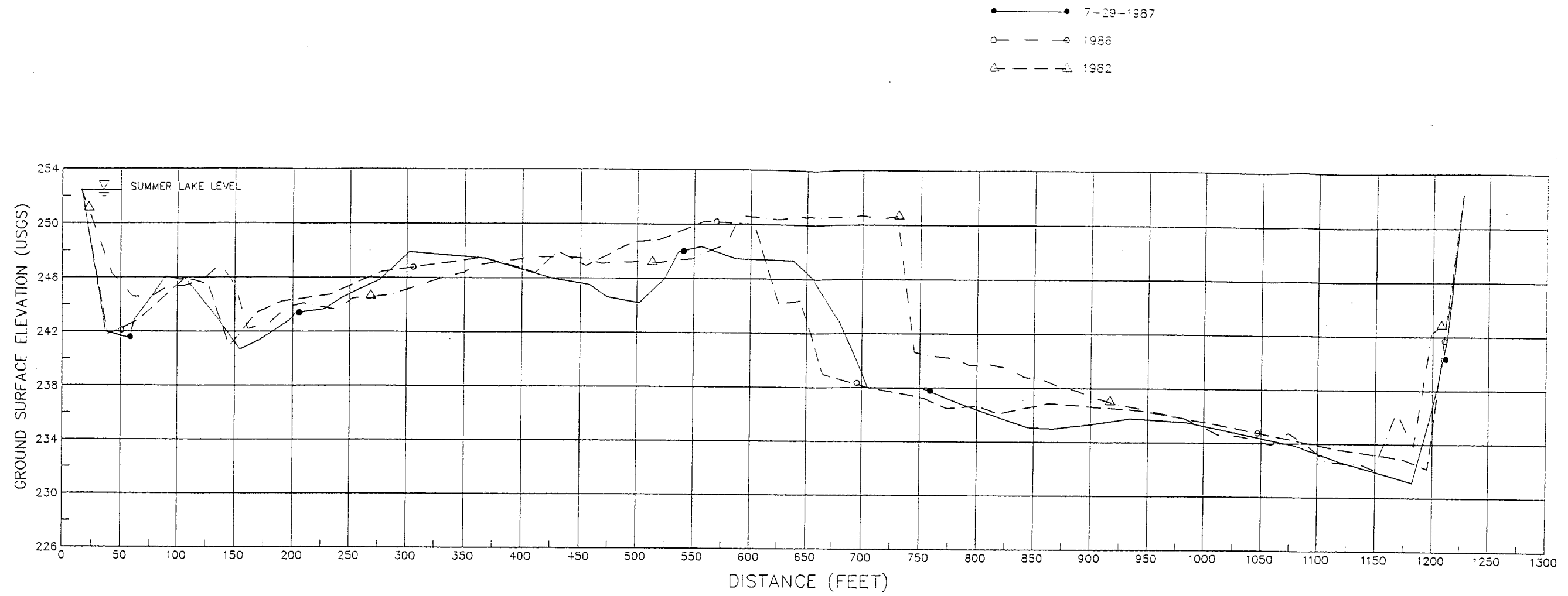
Changes in Cross-Section T-1  
Lake Red Bluff



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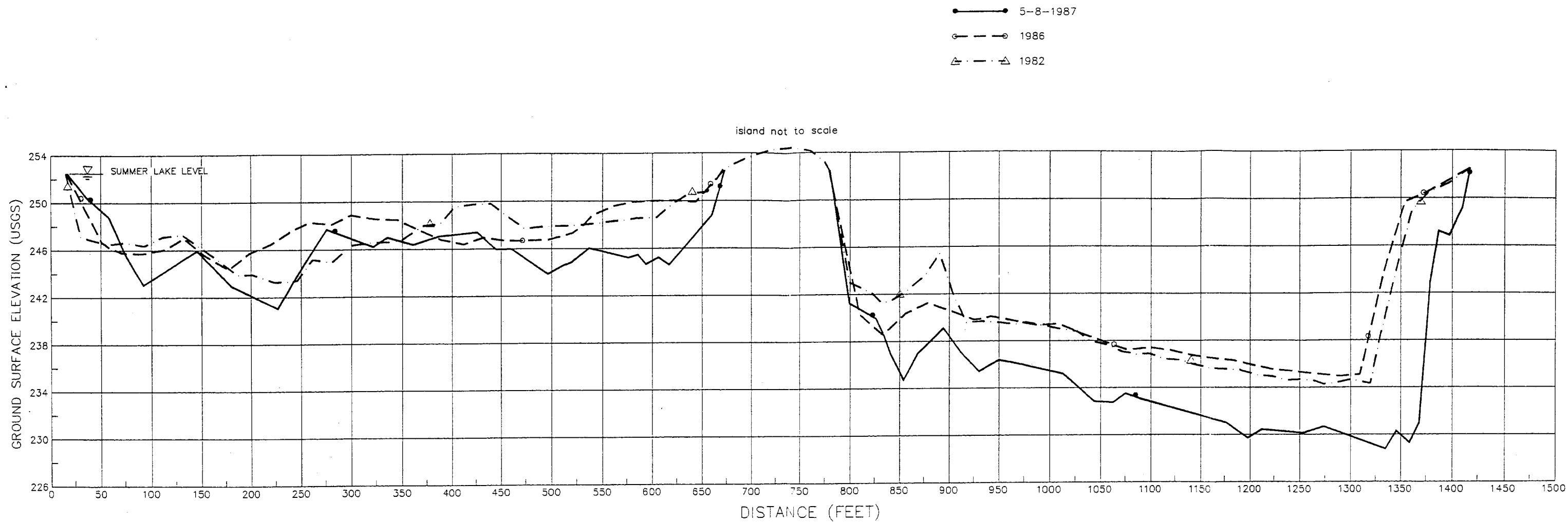
Changes in Cross-Section T-2  
Lake Red Bluff



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Changes in Cross-Section T-3  
Lake Red Bluff

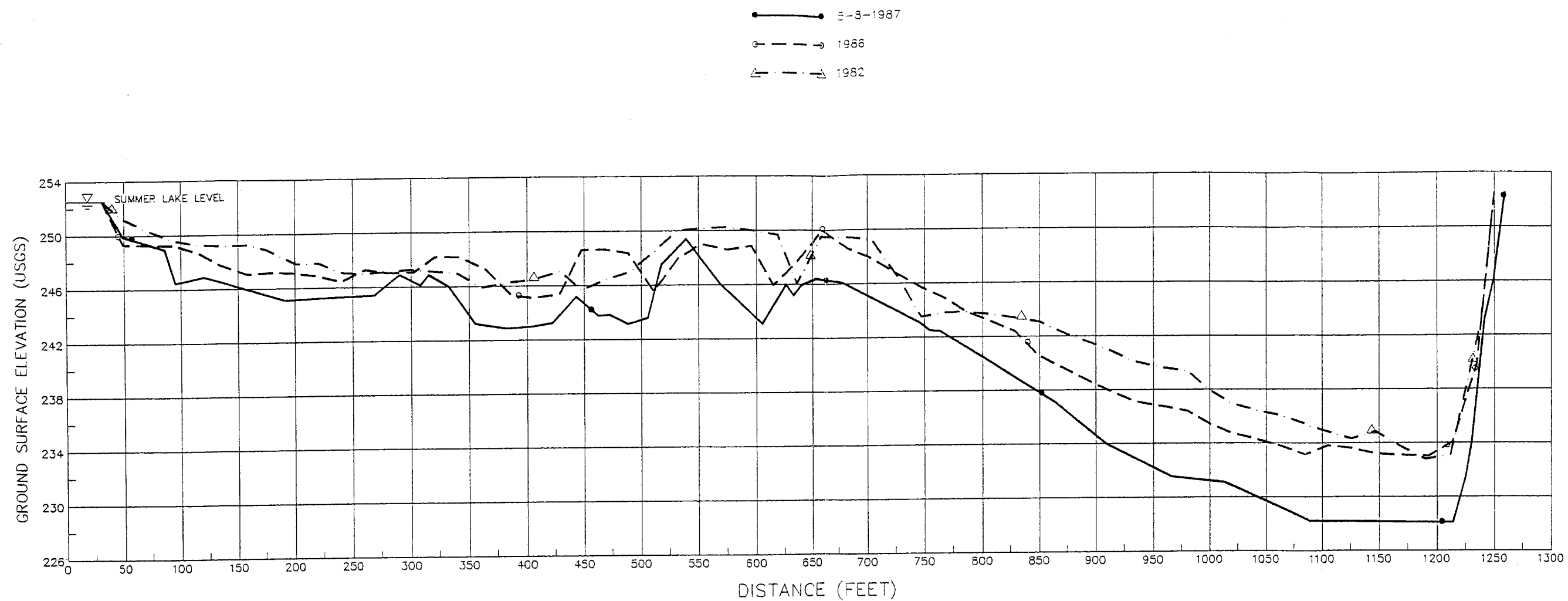


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Changes in Cross-Section T-4  
Lake Red Bluff





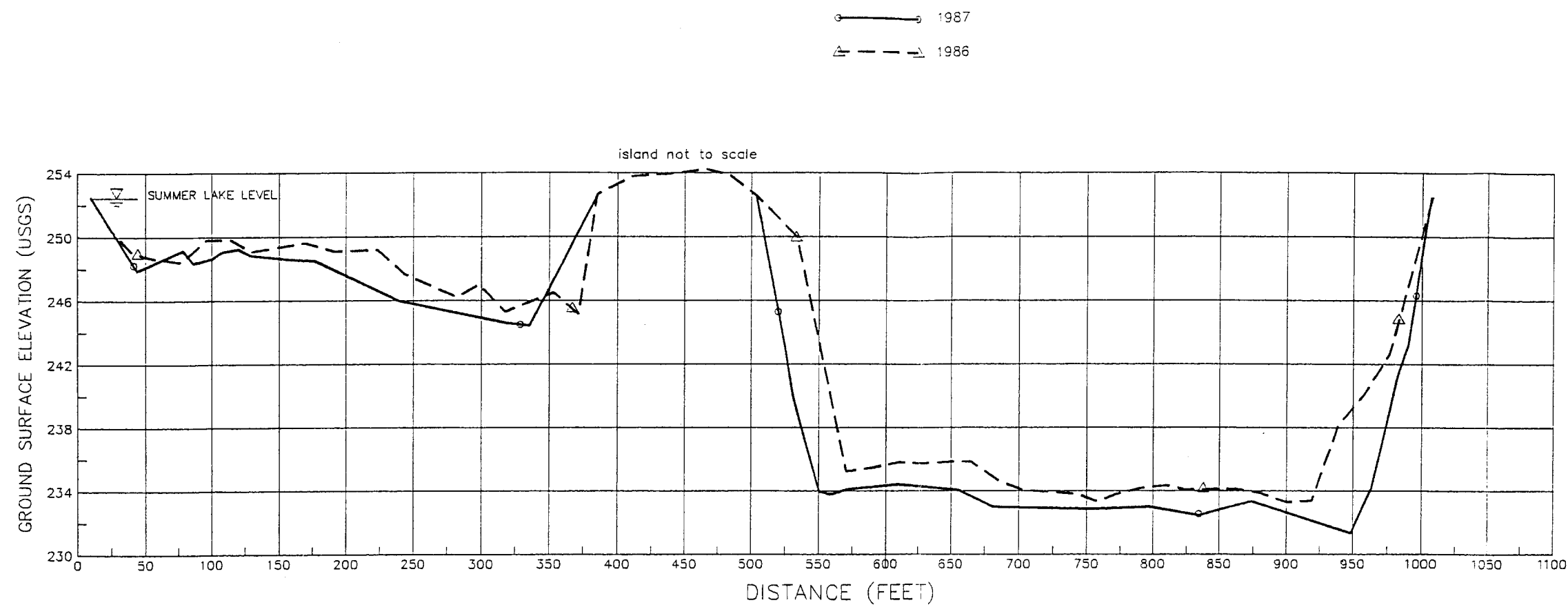
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Changes in Cross-Section T-5  
 Lake Red Bluff



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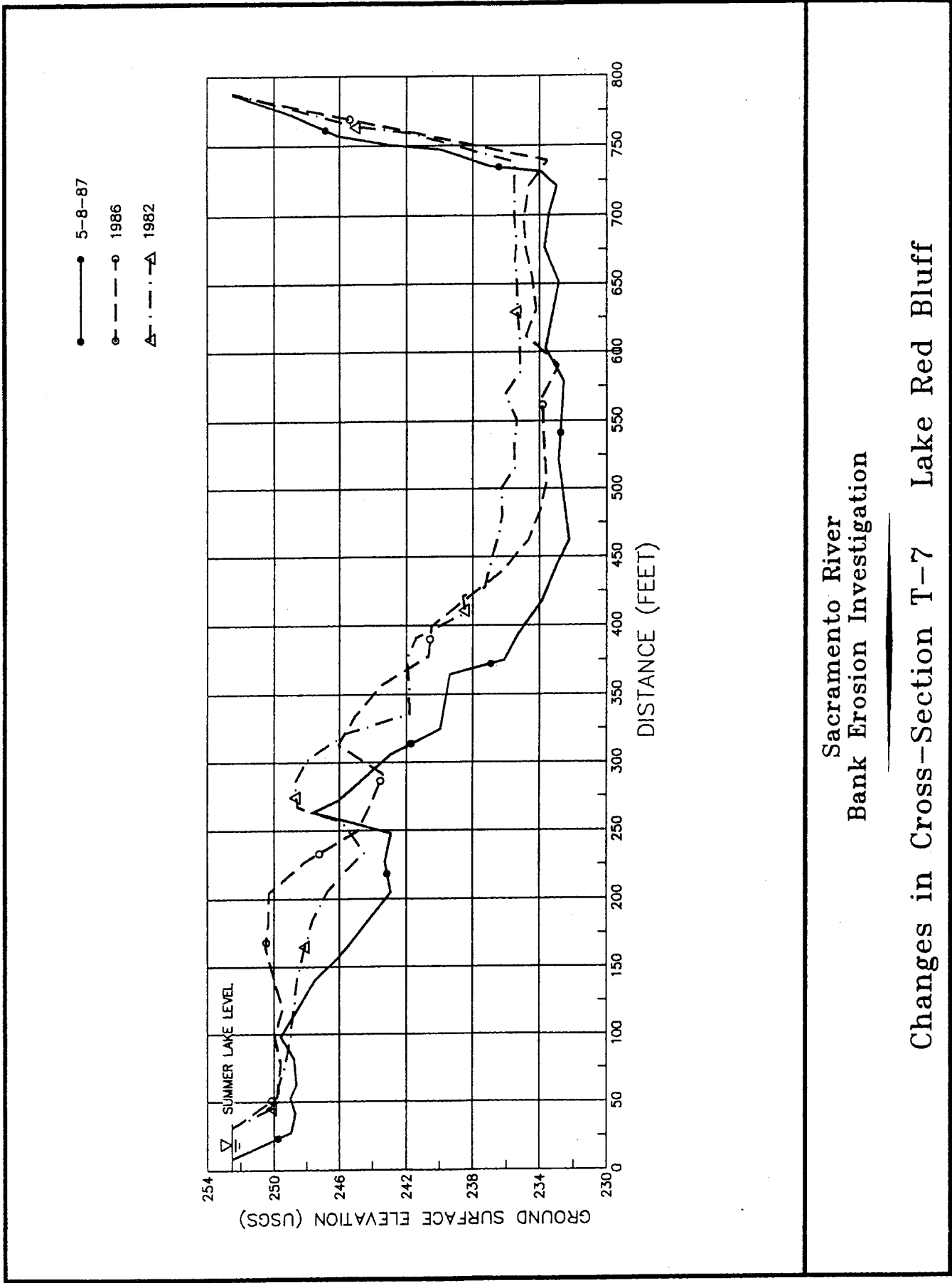
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Sacramento River  
 Bank Erosion Investigation

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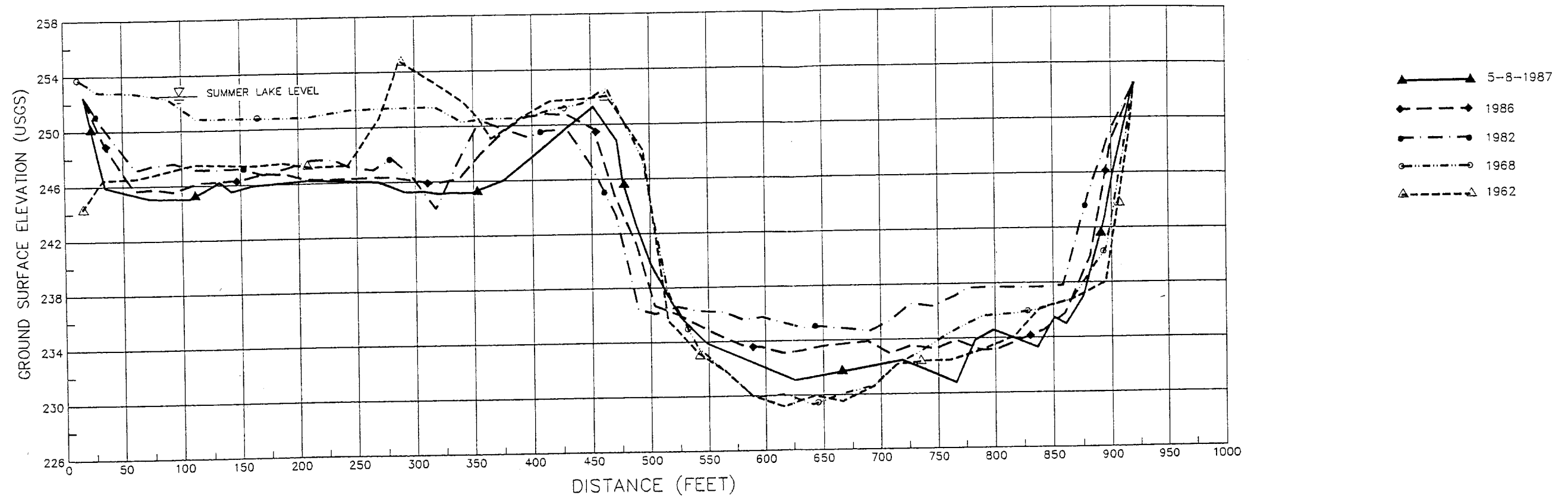
Changes in Cross-Section T-6  
 Lake Red Bluff

Figure 39



Sacramento River  
Bank Erosion Investigation

Changes in Cross-Section T-7 Lake Red Bluff



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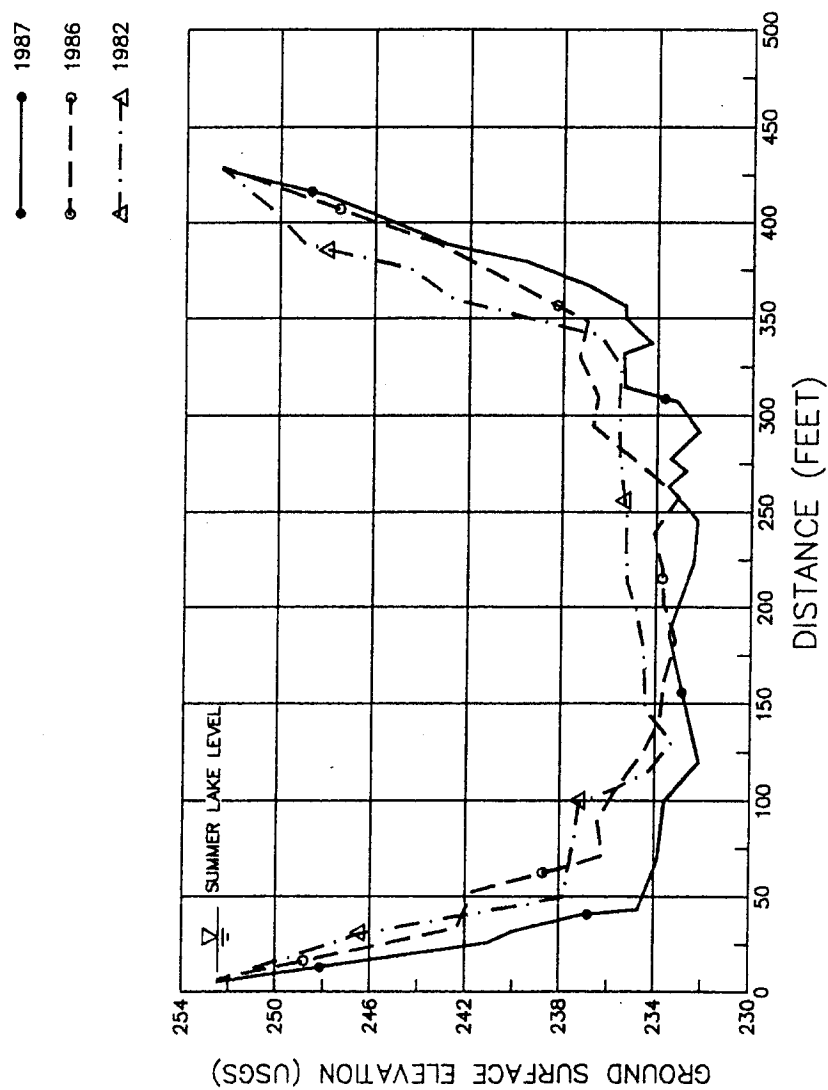
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Sacramento River  
Bank Erosion Investigation

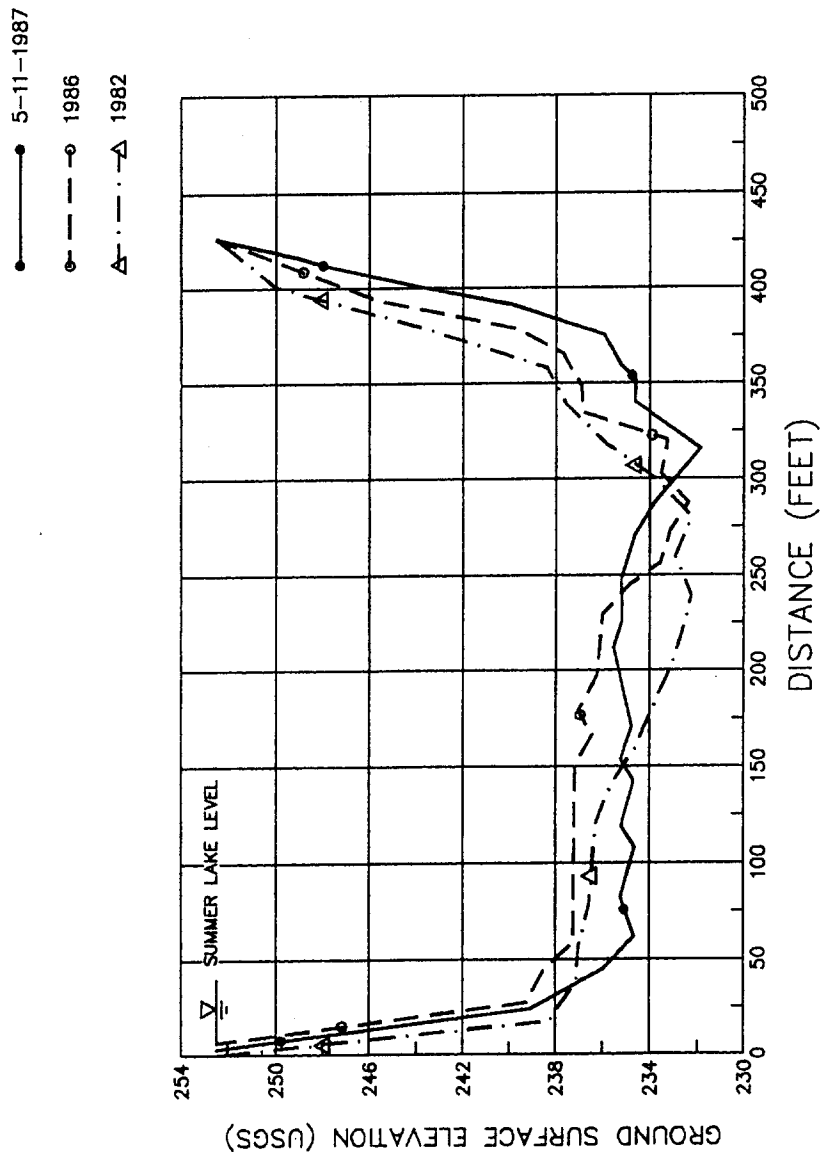
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Changes in Cross-Section T-8  
Lake Red Bluff





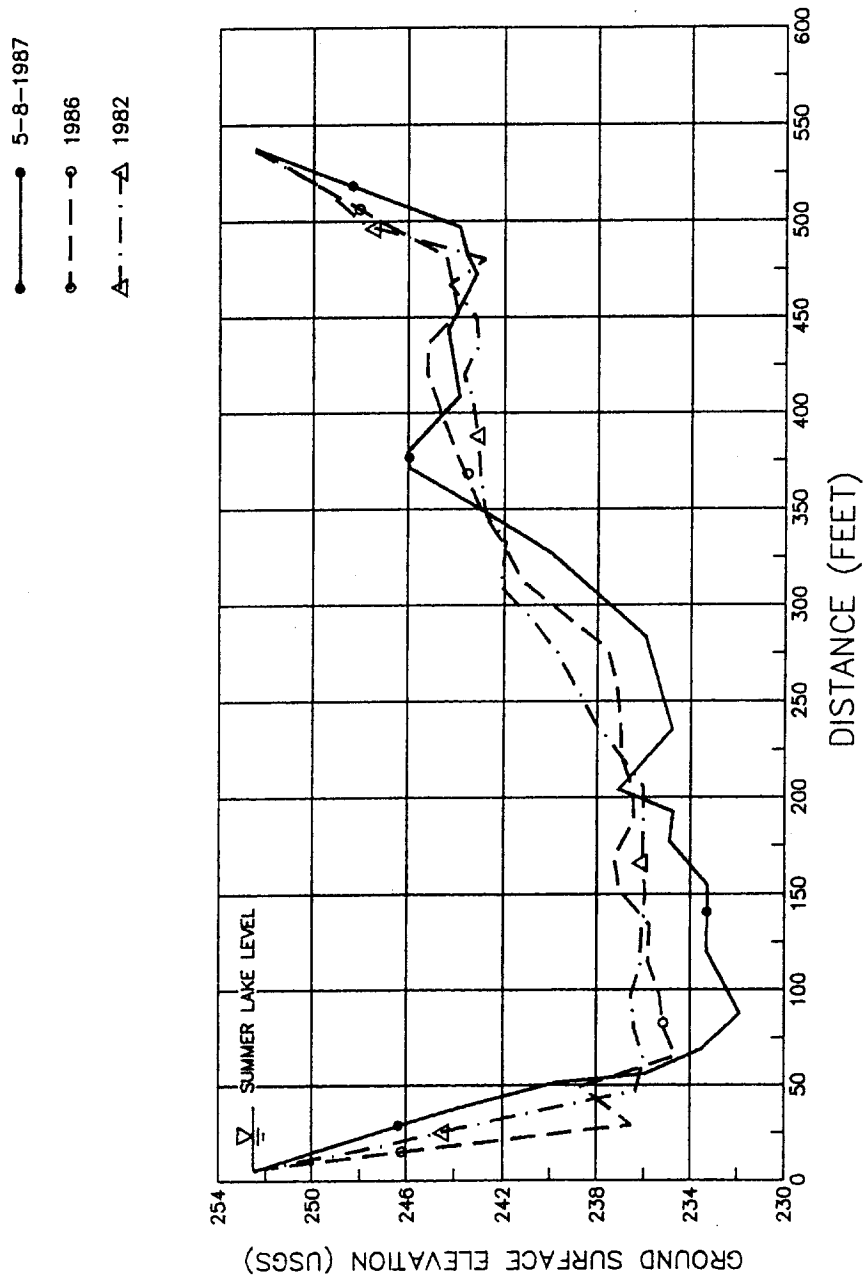
Sacramento River  
Bank Erosion Investigation  
Changes in Cross-Section T-9 Lake Red Bluff



Sacramento River  
Bank Erosion Investigation

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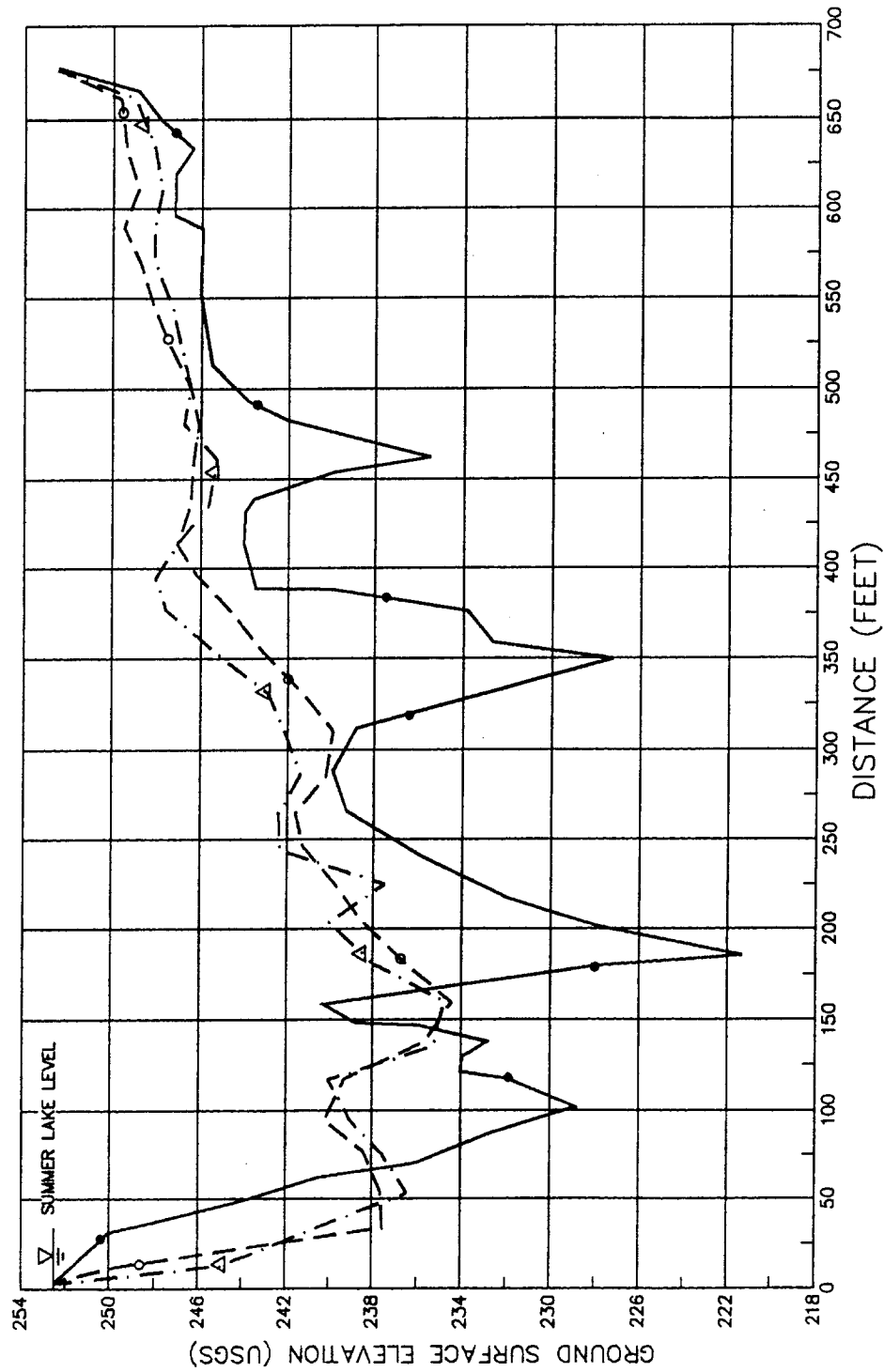
Changes in Cross-Section T-10 Lake Red Bluff



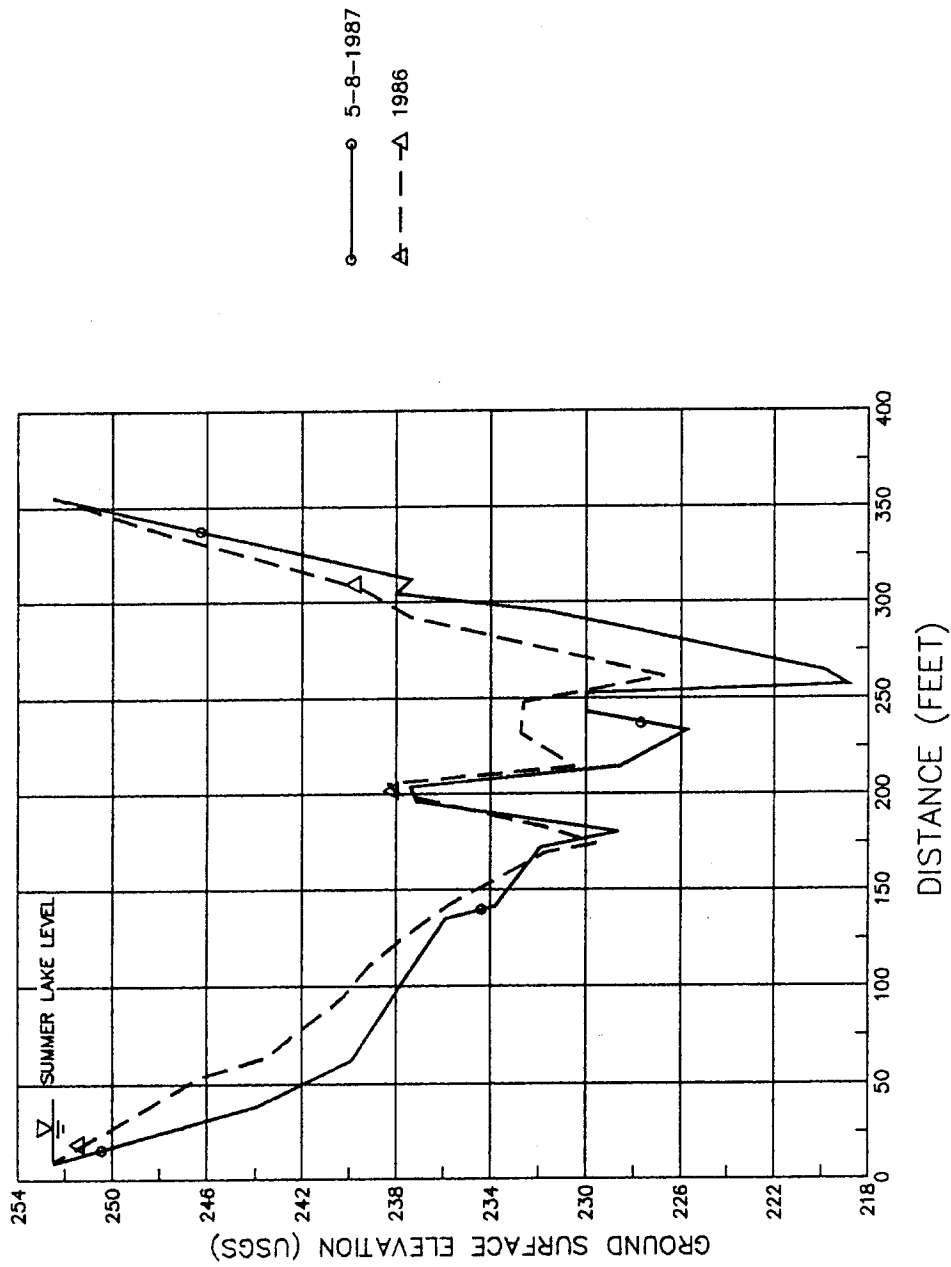
Sacramento River  
Bank Erosion Investigation  
Changes in Cross-Section T-11 Lake Red Bluff



Figure 44



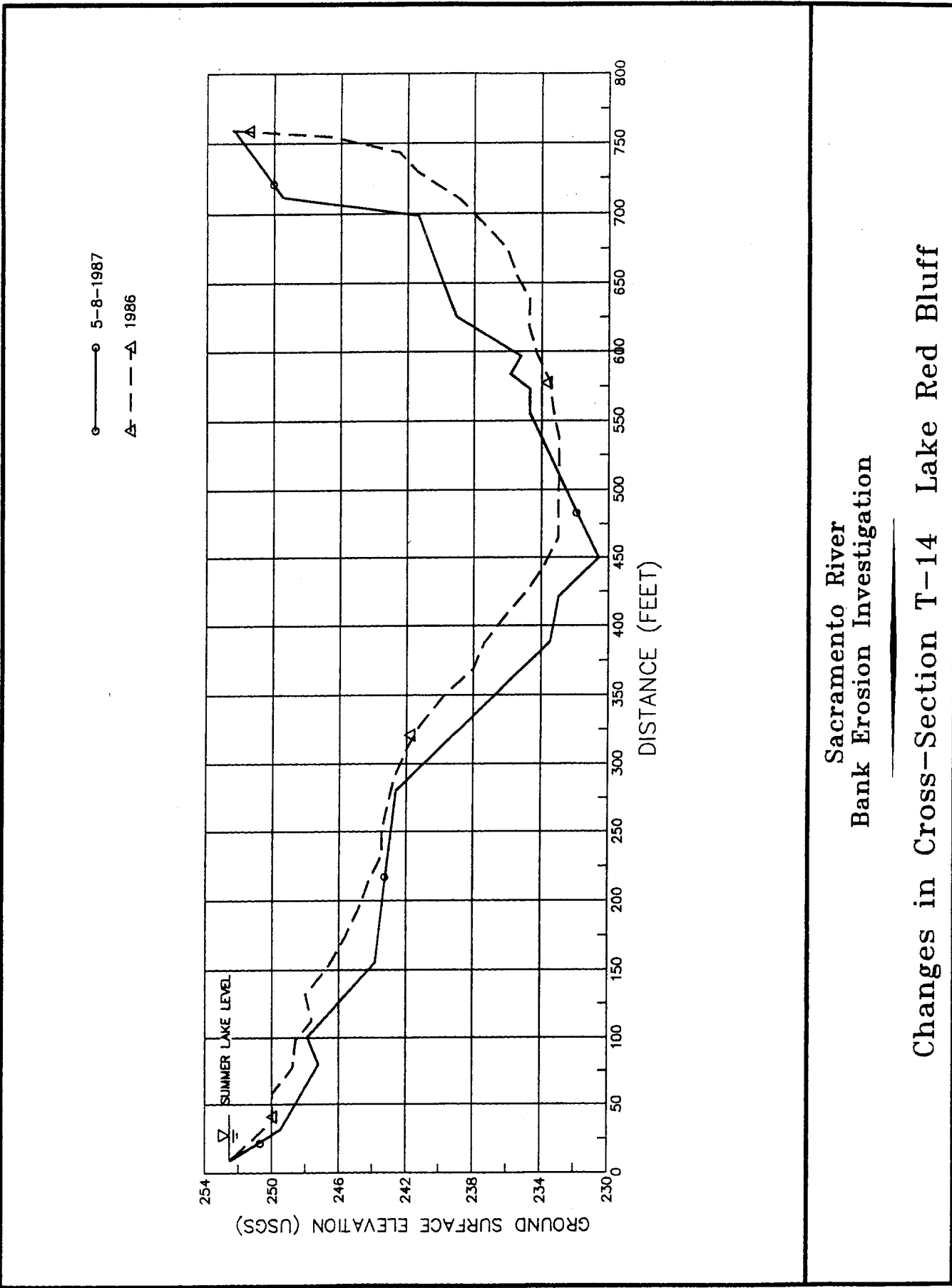
Sacramento River  
Bank Erosion Investigation  
Changes in Cross-Section T-12 Lake Red Bluff



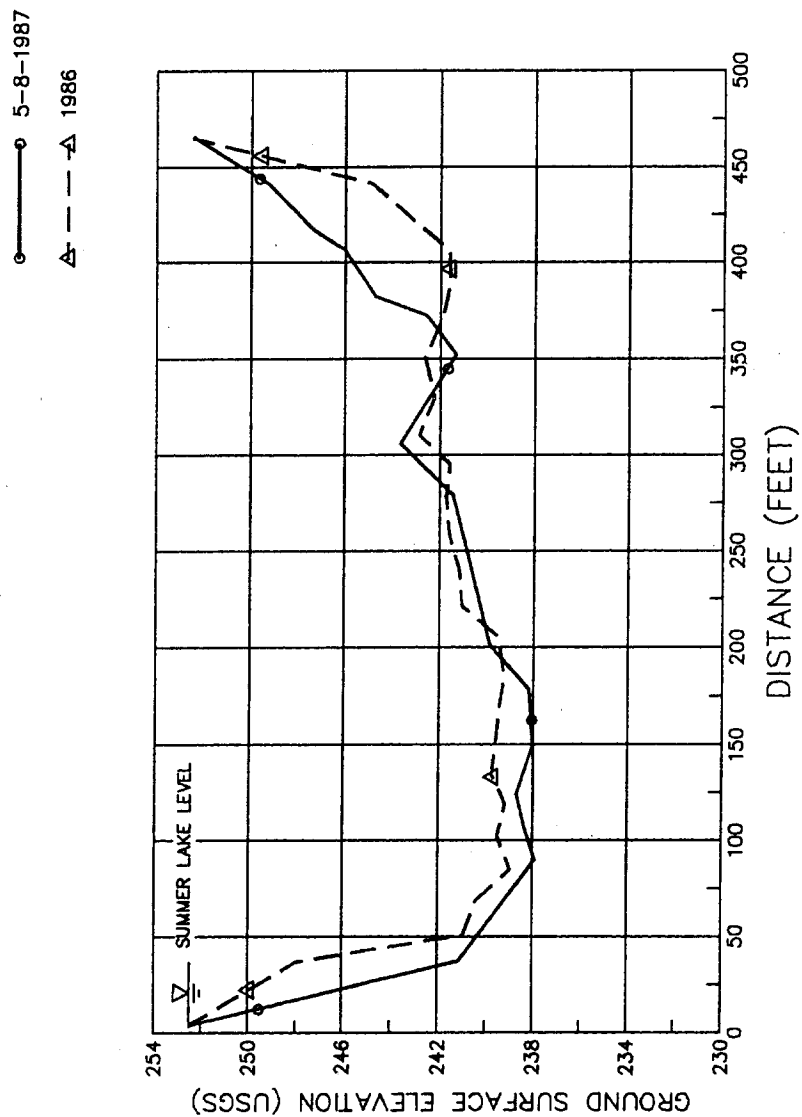
Sacramento River  
Bank Erosion Investigation

Changes in Cross-Section T-13 Lake Red Bluff

Figure 46

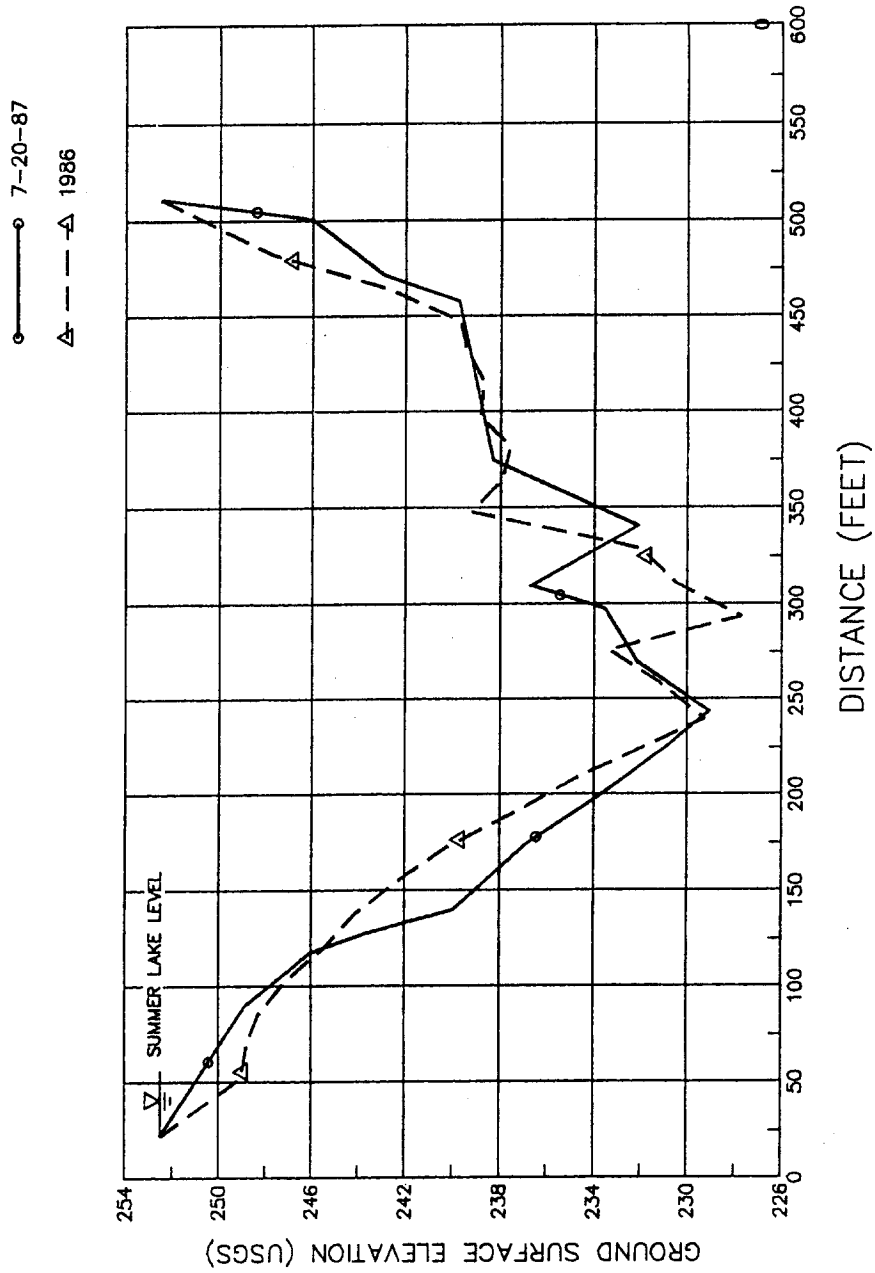


Sacramento River  
Bank Erosion Investigation  
Changes in Cross-Section T-14 Lake Red Bluff



Sacramento River  
Bank Erosion Investigation  
Changes in Cross-Section T-15 Lake Red Bluff

Figure 48



Sacramento River  
Bank Erosion Investigation

Changes in Cross-Section T-16 Lake Red Bluff

**TABLE 11 LAKE RED BLUFF CROSS-SECTIONS**

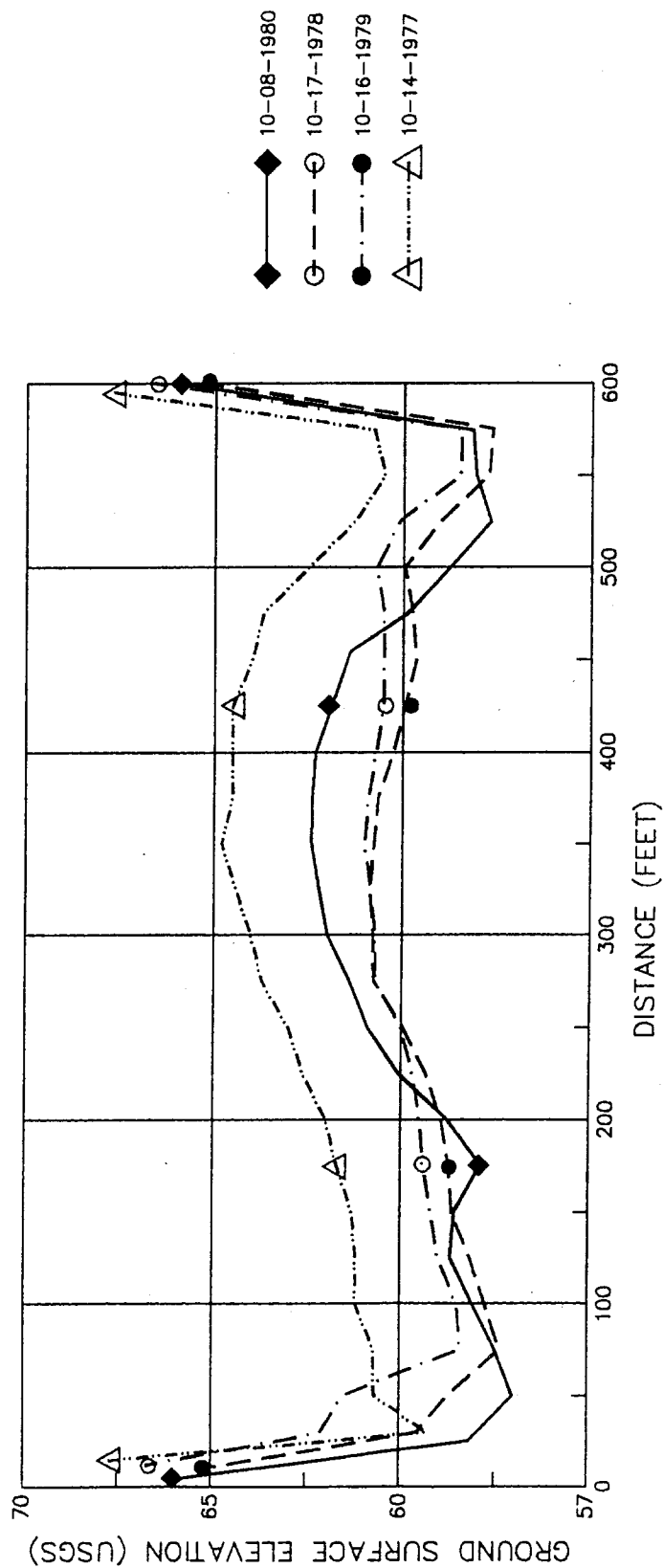
Profile Number	USBR Survey Dates Average Depth, in Feet			DWR Survey Dates Average Depth, in Feet		
	1951	1962	1968	1982	1986	1987
T1				12.37	11.24	12.47
T2	13.39	13.27	13.35	12.99	12.60	14.32
T3				9.53	10.95	11.41
T4				8.90	8.60	12.1
T5				8.07	8.97	11.91
T6					10.5	12.2
T7				10.44	10.85	12.75
T8		9.38	9.17	11.77	13.36	14.30
T9				13.63	14.56	16.59
T10				15.13	14.38	15.90
T11				11.63	11.85	12.7
T12				8.98	9.11	12.58
T13					13.58	16.46
T14					12.12	11.94
T15					10.30	10.32
T16					12.42	12.96

## GAGING STATION CROSS-SECTIONS

Gaging station data from DWR's Sutter Yard Hydrology Section in Sutter, California were used to plot cross-sections. Cross section bottom elevations were collected using a tag line while making instream flow measurements. The elevation of each profile is tied into a gage reading in the vicinity of each site. For that reason, the elevation of each profile has not been established in terms of mean sea level. The resulting data should only be used for comparison purposes. The location of each plot is shown in Figure 20. The years of record are listed in Table 12 below. Figures 49 to 54 show the changes in channel cross-section at the gaging stations. Table 13 shows the change in elevation of gaging station cross-sections.

**TABLE 12 LOCATION OF GAGING STATION CROSS-SECTIONS**

Section Location	Survey Dates
Vina Bridge, 1300 feet below gage	1977, 1978, 1979, 1980
Vina Bridge, 1500 feet below gage	1981, 1982, 1983, 1984
Hamilton City, 1700 feet above gage	1976, 1977, 1978, 1979, 1981, 1982, 1984
Hamilton City, 800 feet above gage	1980, 1985
Ord Ferry, 1300 feet above gage	1977, 1978, 1979, 1980, 1981, 1982
Ord Ferry, 1000 feet above gage	1983, 1984, 1985
Butte City	1957, 1962, 1967

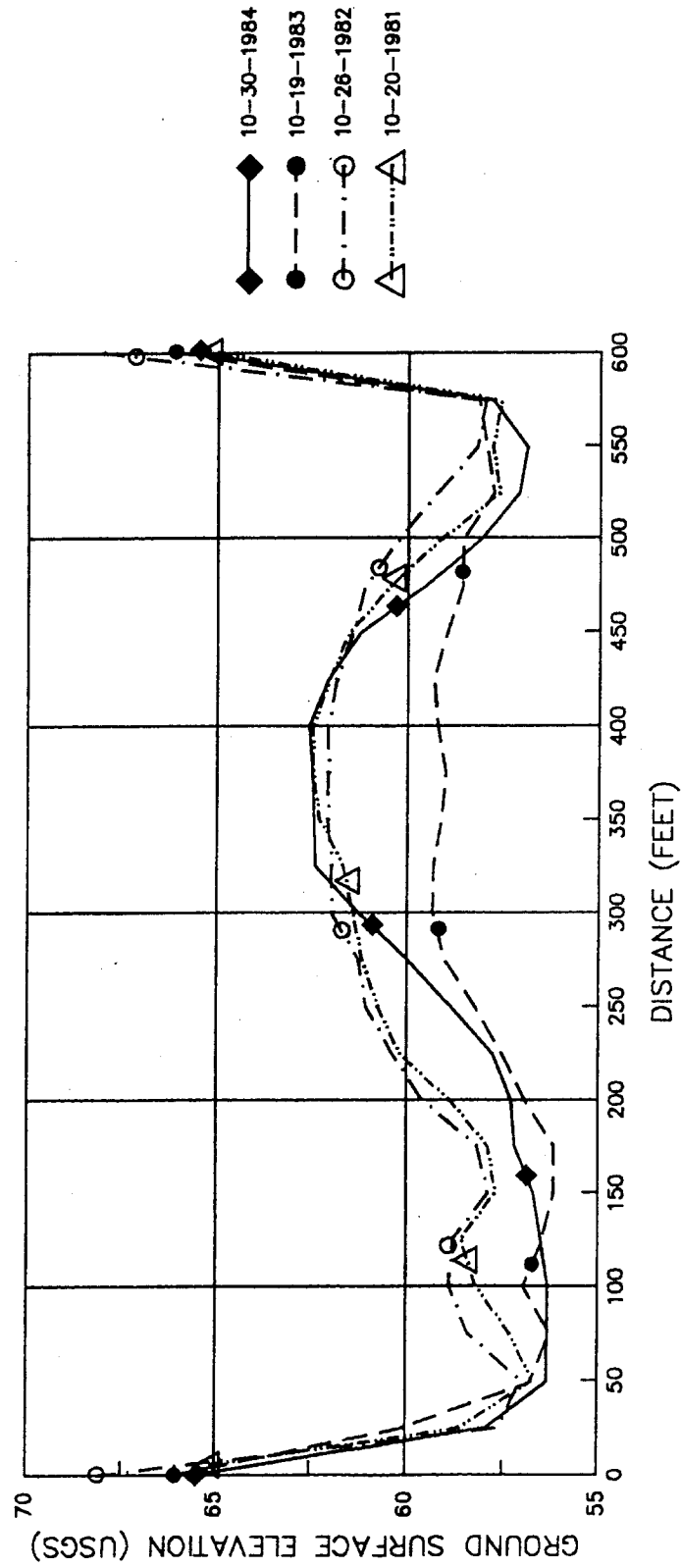


Sacramento River  
Bank Erosion Investigation

Changes in Channel Cross-Section 1300 feet below Vina Gage

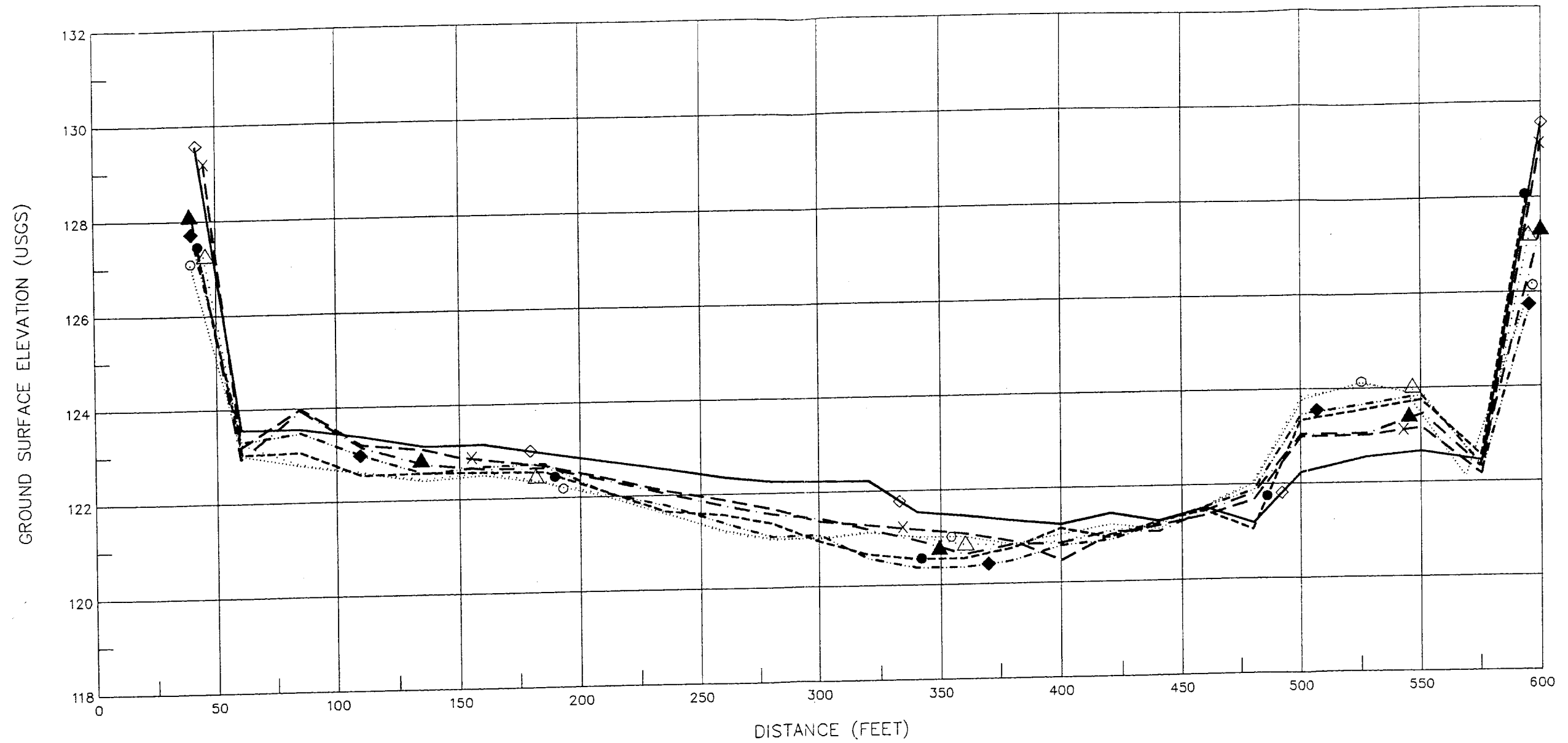


Figure 50



Sacramento River  
Bank Erosion Investigation

Changes in Channel Cross-Section 1500 feet below Vina Gage



- ◇—◇ 10-31-1984
- ×—× 10-27-1982
- ▲—▲ 10-21-1981
- ◆—◆ 10-12-1979
- 10-19-1978
- 10-18-1977
- △—△ 10-13-1976

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### Sacramento River Bank Erosion Investigation

Changes in Channel Cross-Section  
1700 feet above Hamilton City Gage

Figure 52

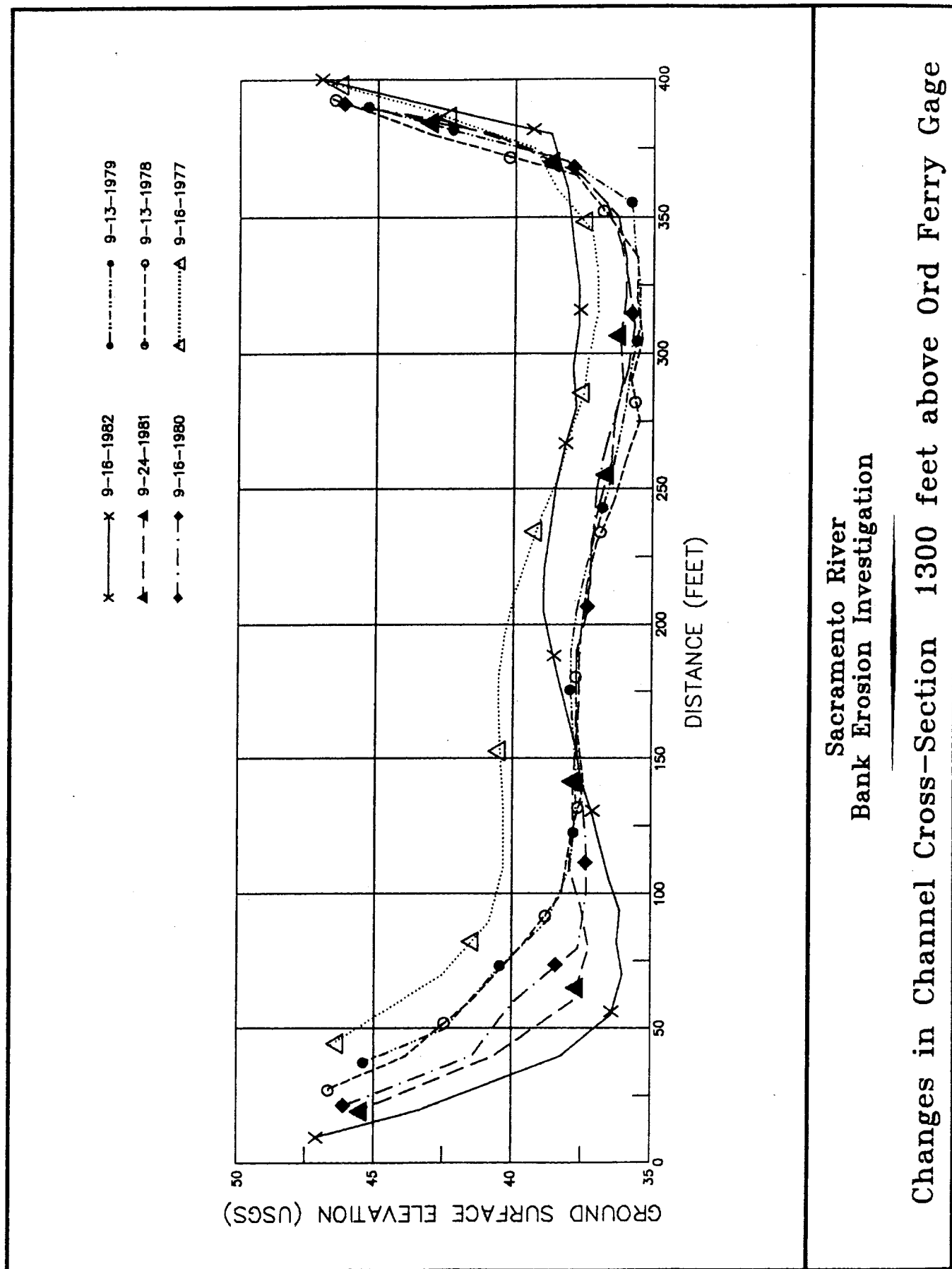
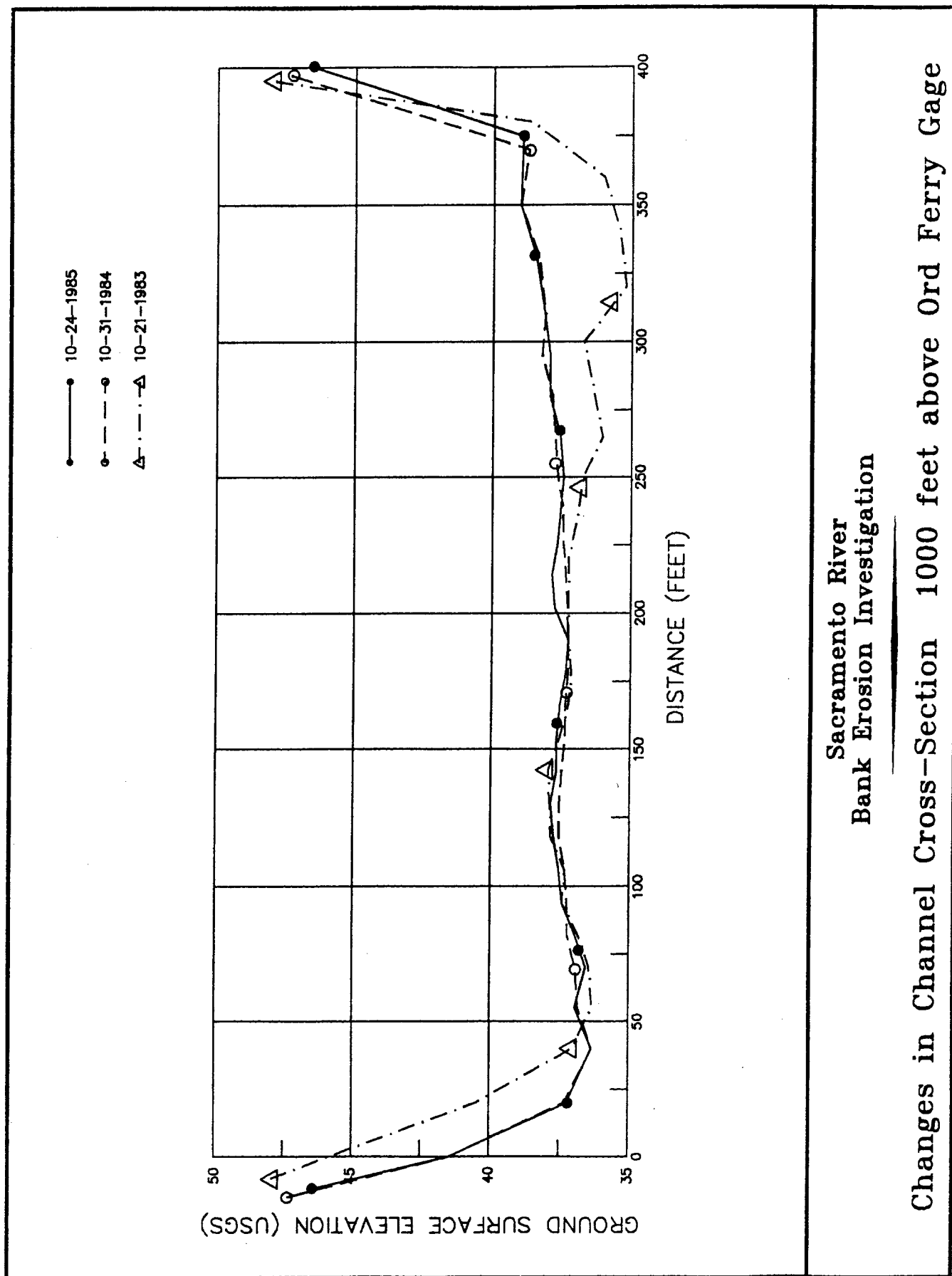


Figure 53



Sacramento River  
Bank Erosion Investigation  
Changes in Channel Cross-Section 1000 feet above Ord Ferry Gage

Figure 54

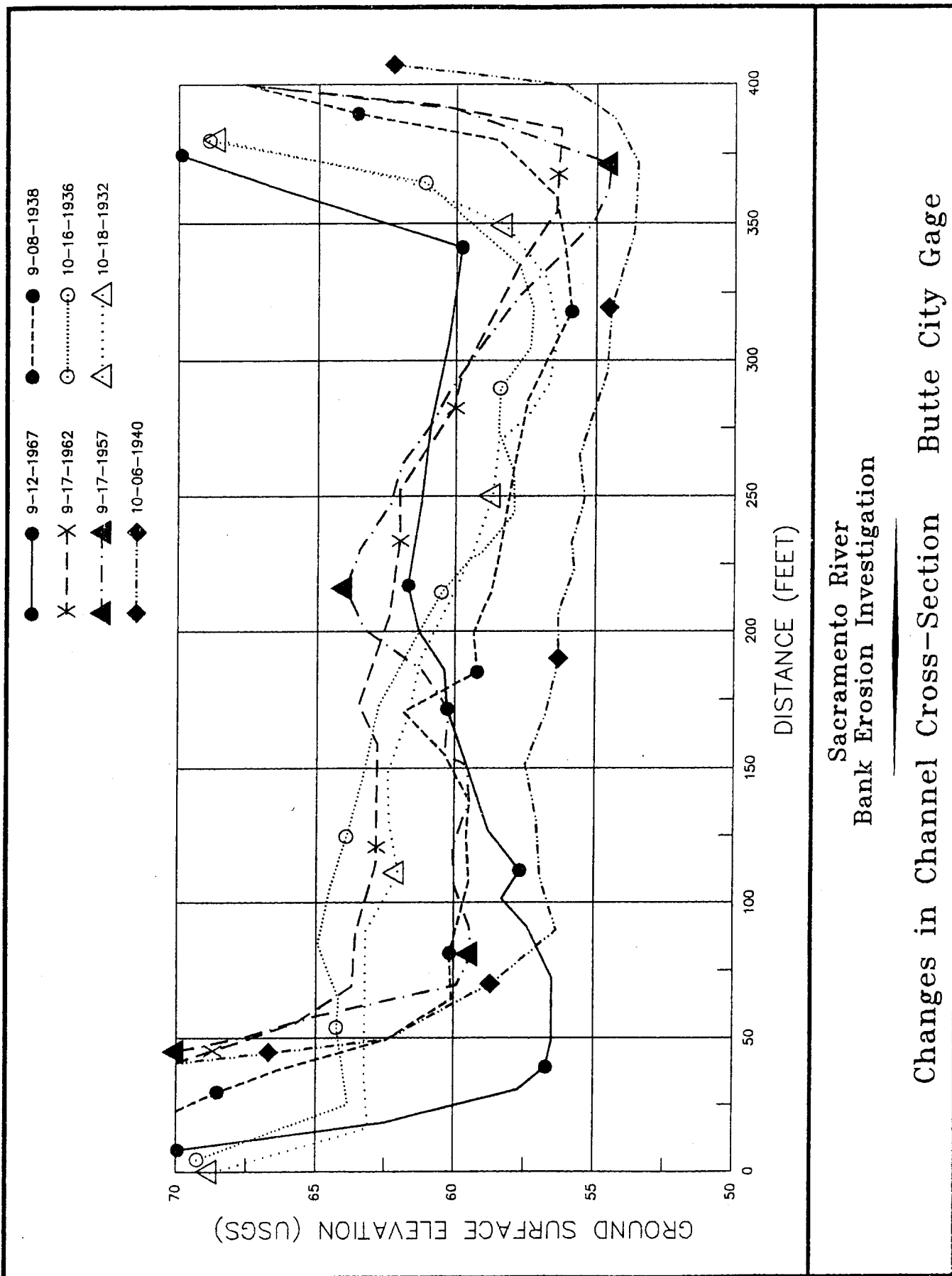


TABLE 13 CHANGE IN ELEVATION OF GAGING STATION CROSS-SECTIONS

years	1000 feet above Ord Ferry Gage		1300 feet above Ord Ferry Gage		Butte City Gage		1300 feet below Vina Gage		1500 feet below Vina Gage		700 feet above Hamilton City Gage	
	Average Depth	Change*	Average Depth	Change*	Average Depth	Change*	Average Depth	Change*	Average Depth	Change*	Average Depth	Change*
1932	-	-	-	-	8.50	0	-	-	-	-	-	-
1936	-	-	-	-	7.68	+0.82	-	-	-	-	-	-
1938	-	-	-	-	9.84	-2.16	-	-	-	-	-	-
1940	-	-	-	-	12.38	-2.54	-	-	-	-	-	-
1957	-	-	-	-	8.47	+3.91	-	-	-	-	-	-
1962	-	-	-	-	7.55	+0.92	-	-	-	-	-	-
1967	-	-	-	-	8.84	-1.29	-	-	-	-	-	-
1976	-	-	-	-	-	-	-	-	-	-	7.23	0
1977	-	-	6.55	0	-	-	5.14	0	-	-	7.31	-0.08
1978	-	-	8.32	-1.77	-	-	7.57	-2.43	-	-	7.30	+0.01
1979	-	-	8.35	-0.03	-	-	8.30	-0.73	-	-	7.32	-0.02
1980	-	-	8.69	-0.34	-	-	7.93	+0.37	-	-	-	-
1981	-	-	8.85	-0.16	-	-	-	-	8.16	0	7.22	+0.10
1982	-	-	8.70	+0.15	-	-	-	-	7.80	+0.36	7.10	+0.12
1983	10.05	0	-	-	-	-	-	-	9.69	-1.89	-	-
1984	9.67	+0.38	-	-	-	-	-	-	8.92	+0.77	6.91	+0.19
1985	9.71	-0.04	-	-	-	-	-	-	-	-	-	-

\* Change in average elevation of cross-section, in feet. + Aggradation - Degradation

## THALWEG DEPTHS AND RIVER WIDTHS NEAR ERODING AND RIPRAPPED BANKS

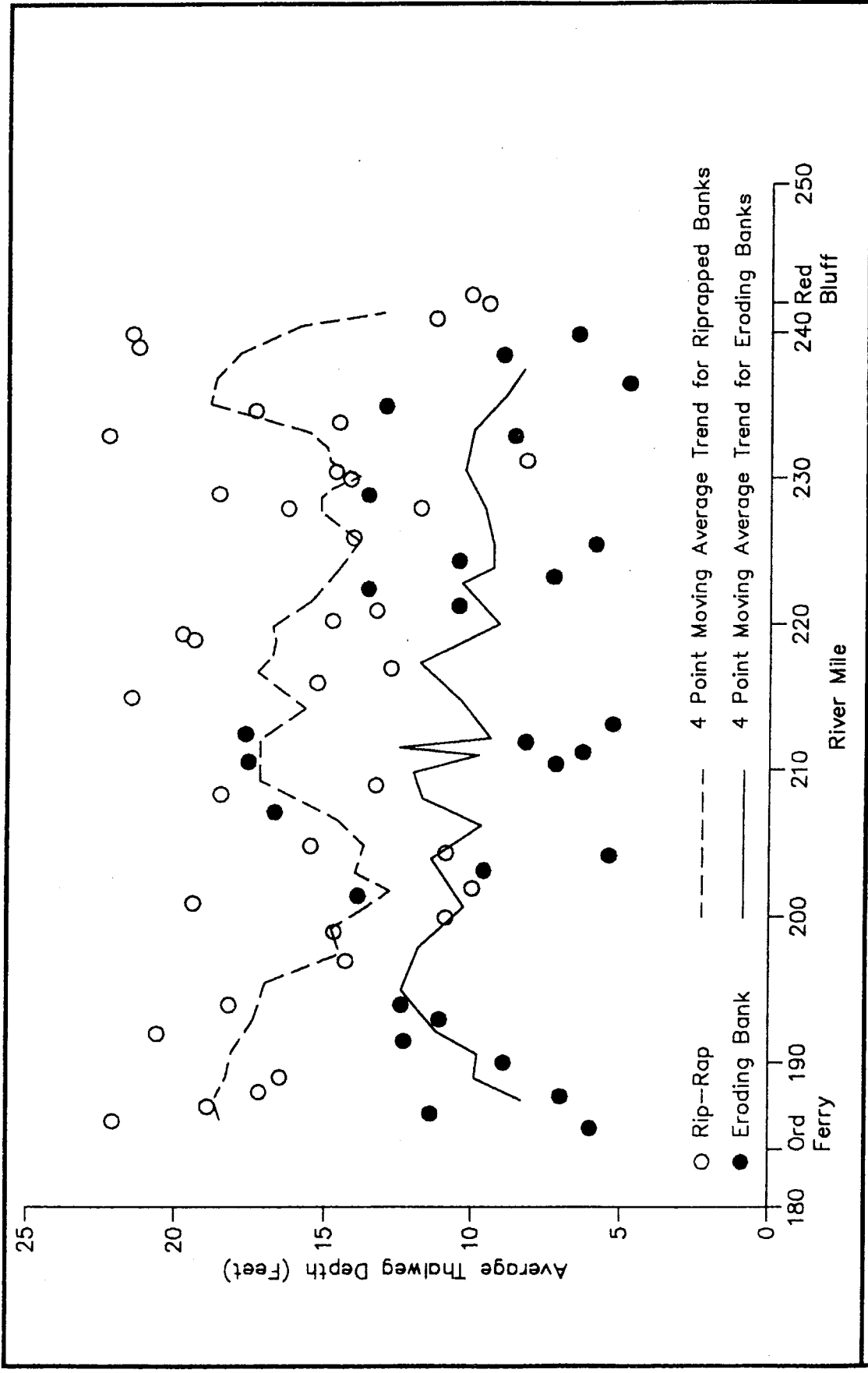
The Department of Water Resources (1984) theorized that bank protection would cause the channel to narrow and deepen. When a channel is stabilized, it will no longer erode its banks but will erode its bed. Deposition will continue on the inside of the bend, causing the channel to narrow and deepen. Such a channel will have less hydraulic diversity and salmon spawning area.

In conjunction with DWR's bank erosion monitoring program, thalweg depths were measured in 1987 opposite 30 eroding banks between Red Bluff and Ord Ferry. Depths were obtained by using a sonar depth-finding instrument mounted on the back of a jet boat. Individual surveys were started at the downstream end of the site and continuous soundings recorded as the boat followed a sinusoidal path across the thalweg adjacent to each bank. The resultant strip chart recordings were analyzed and an average thalweg depth for each site was obtained. The same procedure was used for measuring thalweg depths opposite 37 riprapped sites between Red Bluff and Ord Ferry. These data were entered into spreadsheets for analysis. Eroding bank and riprapped thalweg depths were then plotted by river mile. Four-point moving average trends were then derived and plotted for both erosion and riprap sites. The area between these two curves was divided by measured river length to yield mean river depth over the measured Sacramento River reach. Figure 55 shows that in 1987 the mean thalweg along riprapped banks average 6 feet deeper than comparable eroding banks. The average thalweg depth for riprap has a mean of 15.8 feet, ranging from a minimum of 8 feet to a maximum of 23 feet. The average thalweg depth for eroding banks has a mean of 10.0 feet, ranging from a minimum of 5 feet to a maximum of 18 feet.

A similar study was done in 1991 to test the results of our 1987 study. The resulting plot, shown on Figure 56, is remarkably similar to the 1987 results.

River channel widths were measured every 400 feet from 1987 aerial photos between Red Bluff and Ord Ferry. River widths opposite eroding and riprapped banks were averaged to yield a mean width opposite each eroding bank and a mean width opposite each riprapped bank. These mean values were then plotted by river mile (Figure 57). Four-point-moving-average trends were also calculated and plotted. The area between these two curves was divided by measured river length to yield mean river width over the measured Sacramento reach. Widths opposite erosion sites are generally greater than at riprap sites by an average of 65 to 90 feet, depending on how the average is calculated. Eroding banks have a mean of 480 feet, ranging from a minimum of 325 feet to a maximum of 600 feet. Riprap widths were narrower, with a mean of 410 feet, ranging from a minimum of 290 feet to a maximum of 600 feet. The difference in widths appears to remain fairly constant from Ord Ferry (RM 184.3) to RM 223; upriver from there, the difference decreases until from RM 235 to Red Bluff, it is essentially nonexistent.

Figure 55

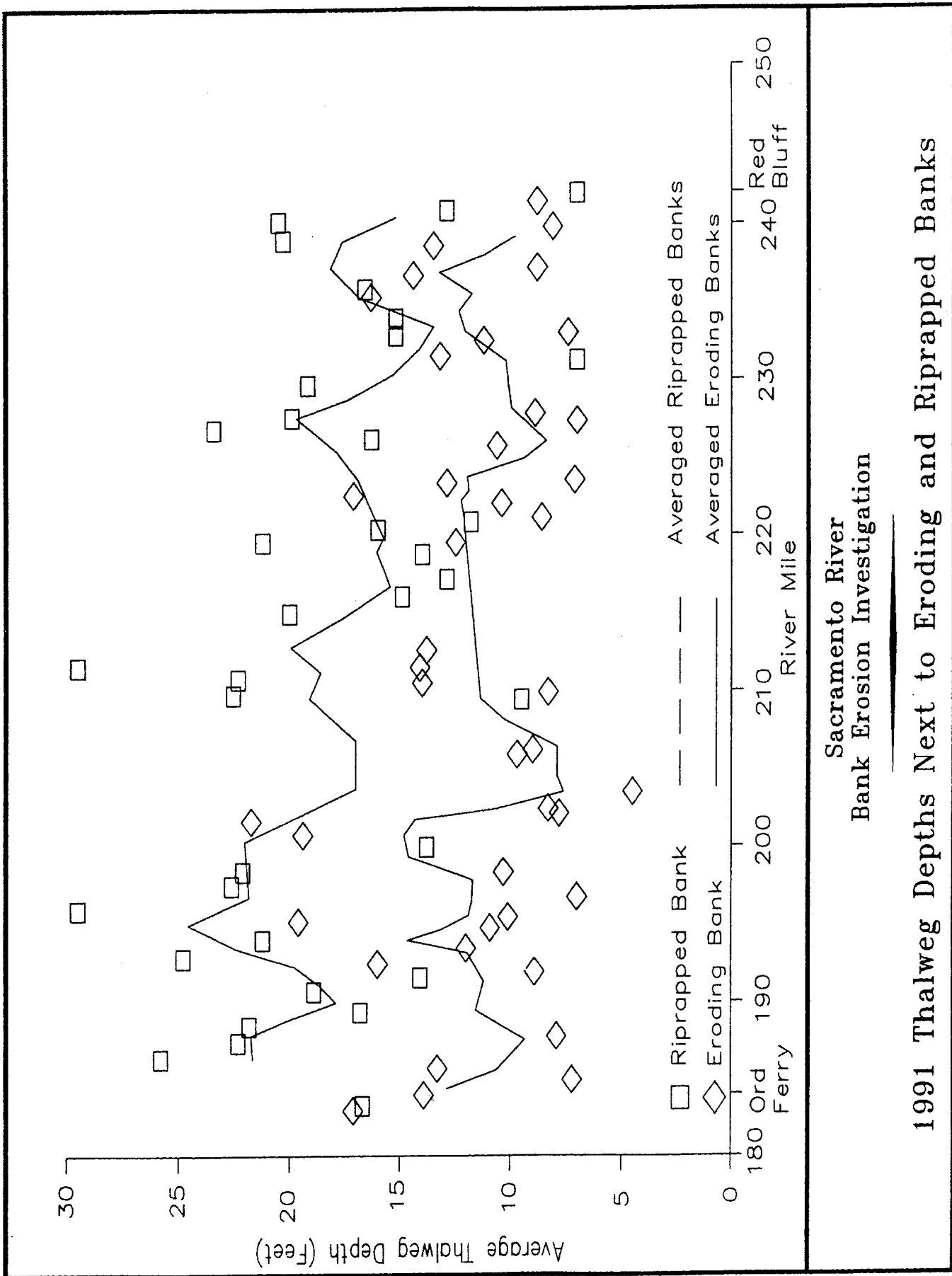


**Sacramento River  
Bank Erosion Investigation**

**1987 Thalweg Depths Next to Eroding and Riprapped Banks**

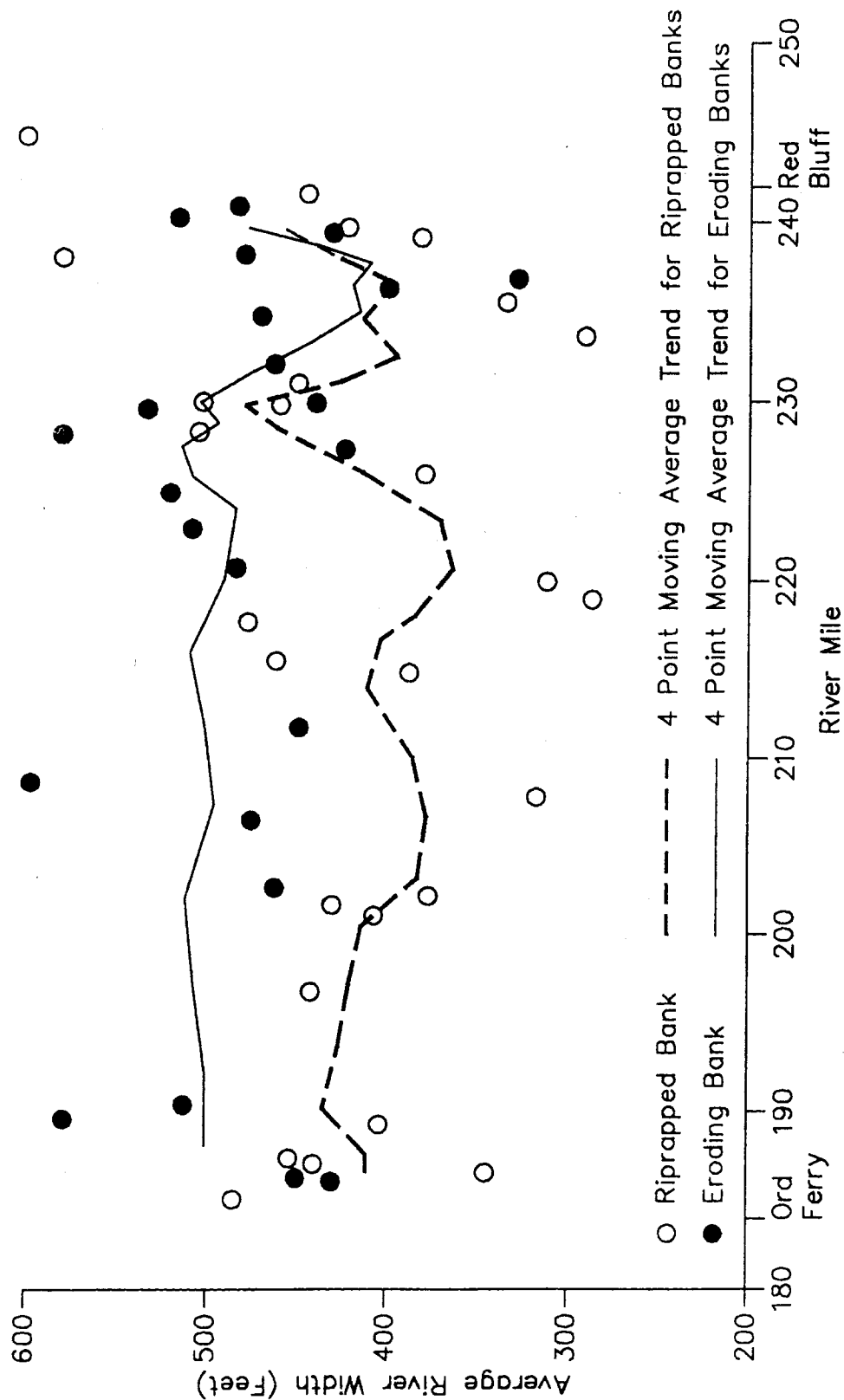


Figure 56



Sacramento River  
 Bank Erosion Investigation  
 1991 Thalweg Depths Next to Eroding and Riprapped Banks

Figure 57



### Bank Erosion Investigation

1987 River Widths Next to Eroding and Riprapped Banks

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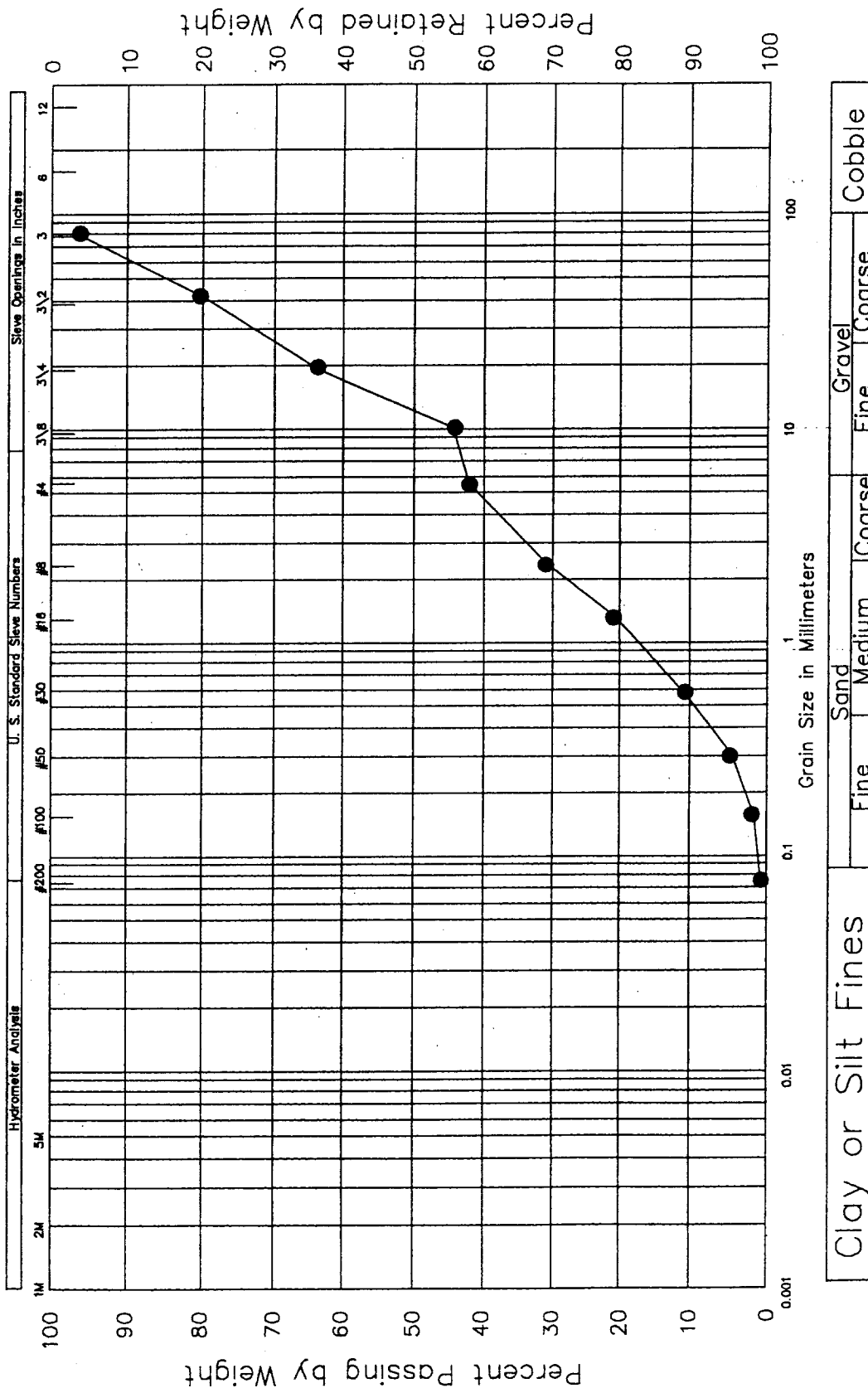
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**APPENDIX A**  
**SACRAMENTO RIVER BANK BULK SAMPLES**

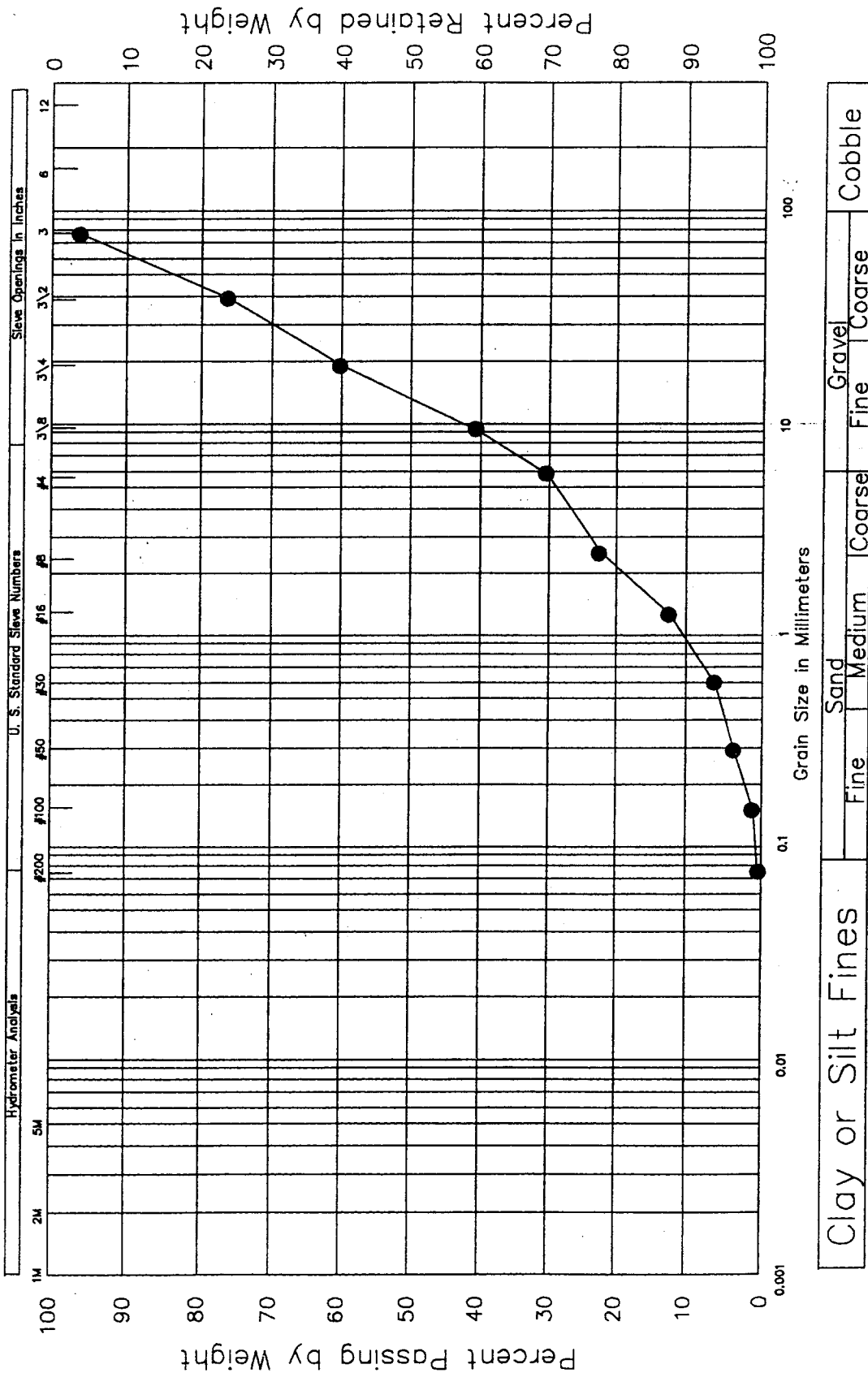
# Mechanical Analysis Graph



MECHANICAL ANALYSIS OF THE  
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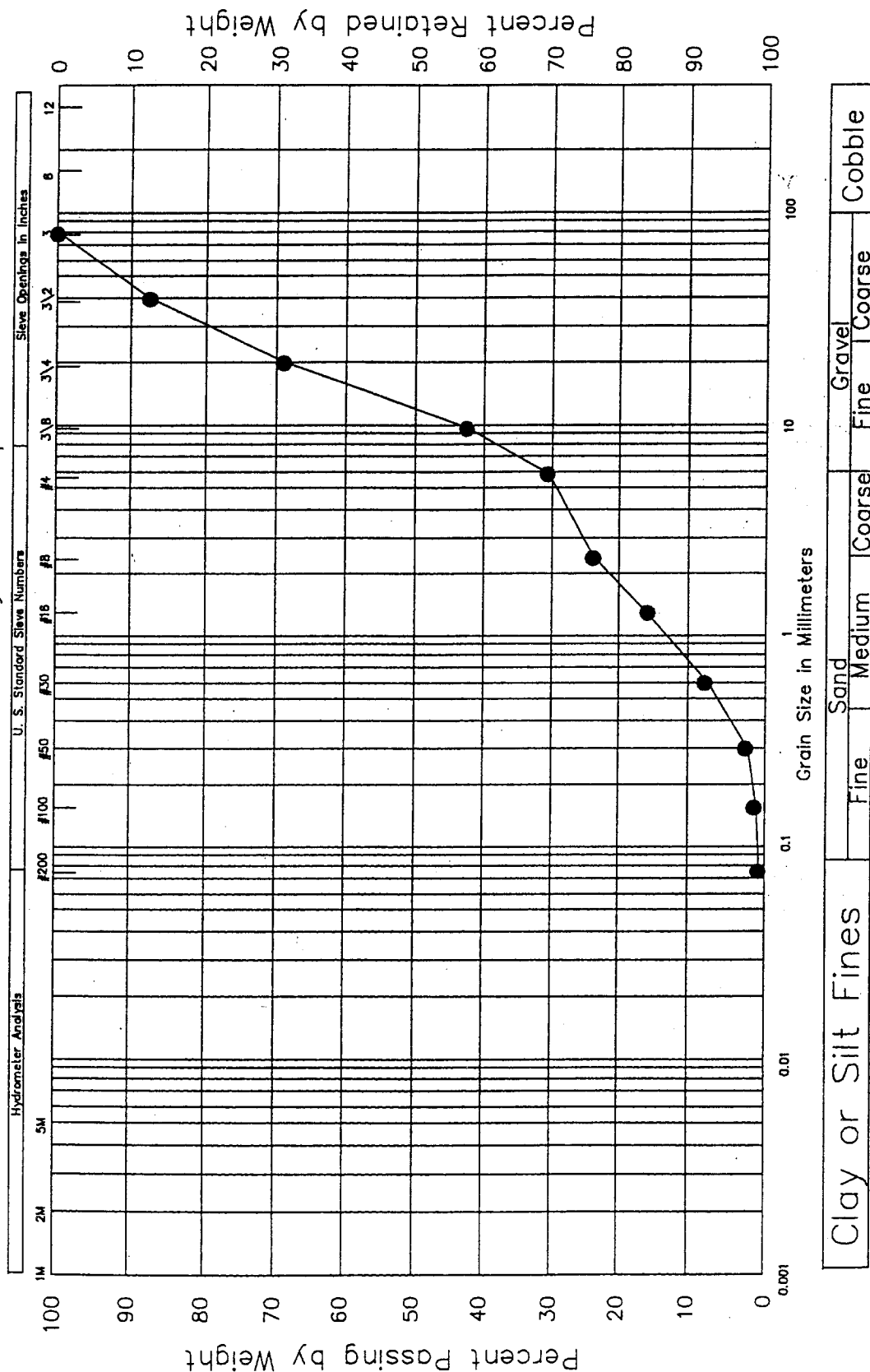


# Mechanical Analysis Graph



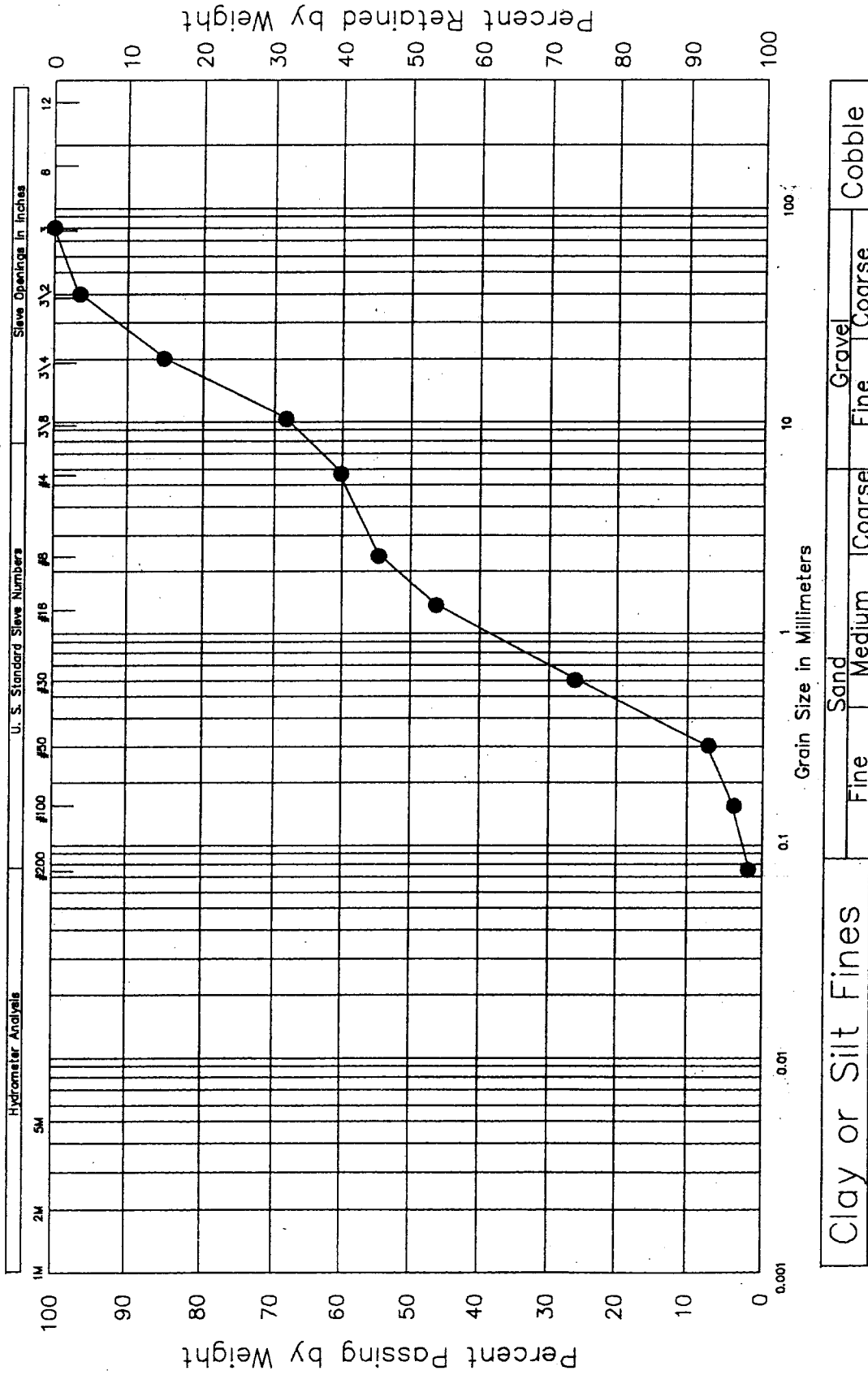
MECHANICAL ANALYSIS OF THE  
TOOMES CREEK #1 EROSION SITE

# Mechanical Analysis Graph



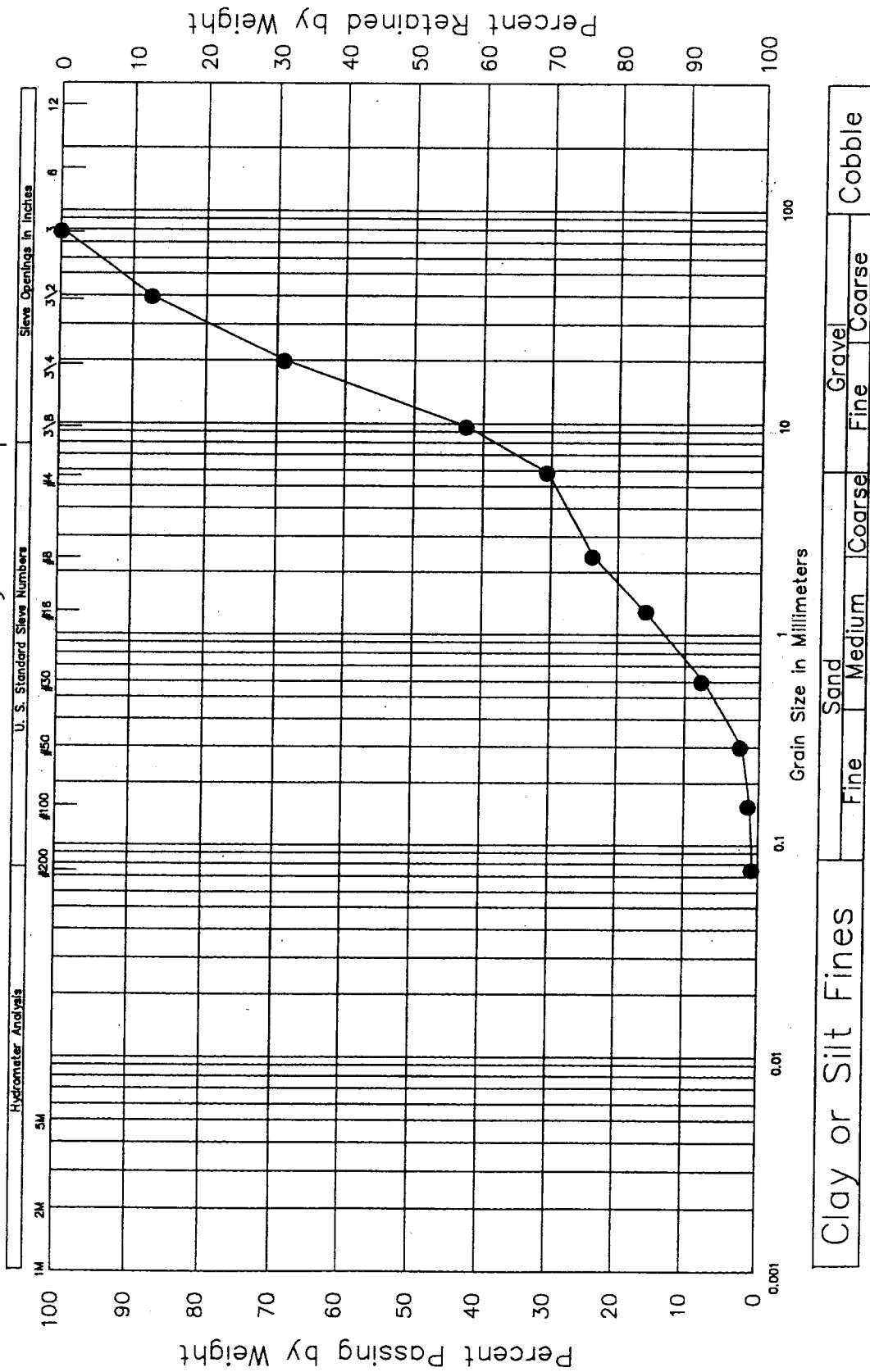
MECHANICAL ANALYSIS OF THE  
PALISADES EROSION SITE

# Mechanical Analysis Graph



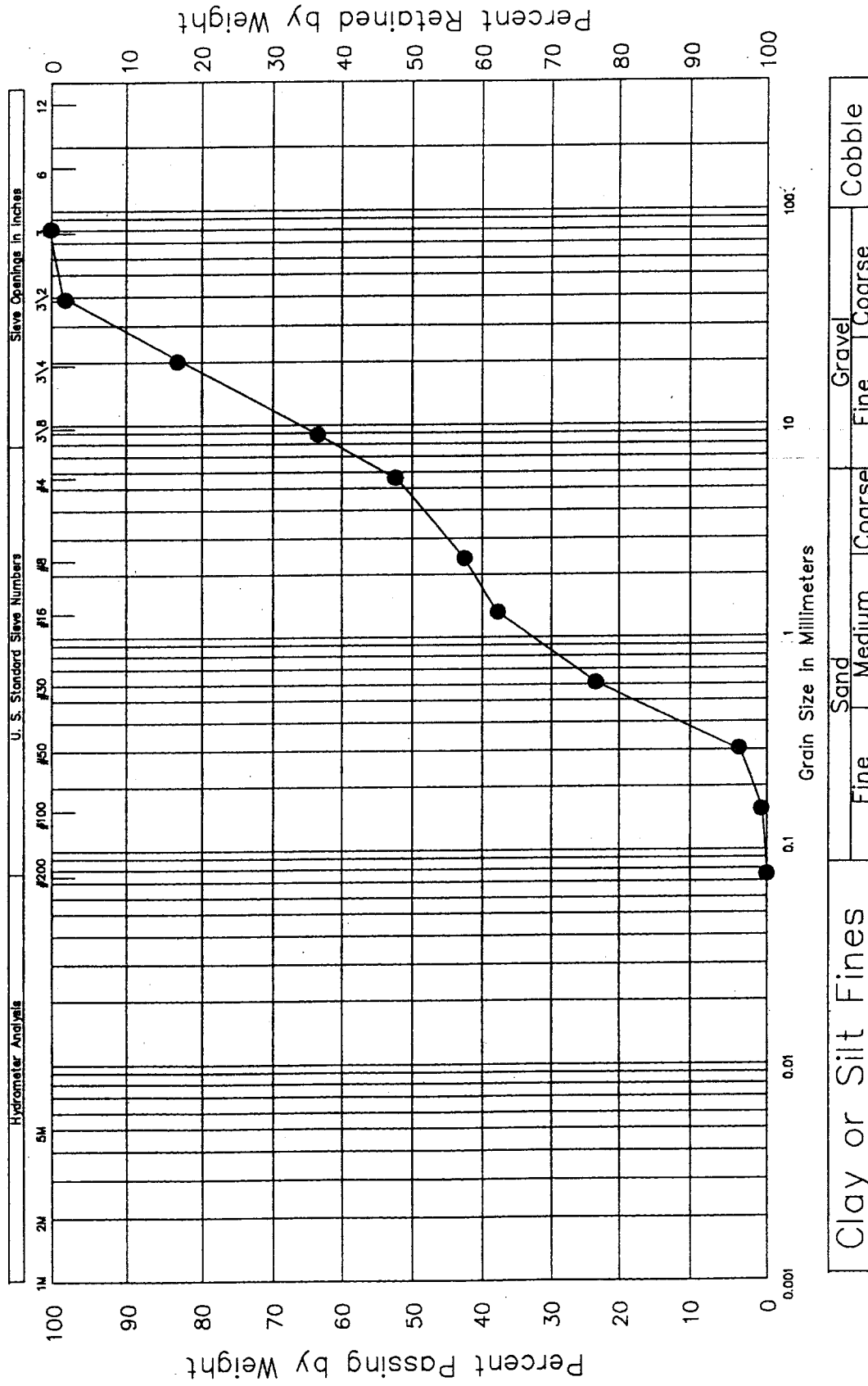
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# Mechanical Analysis Graph



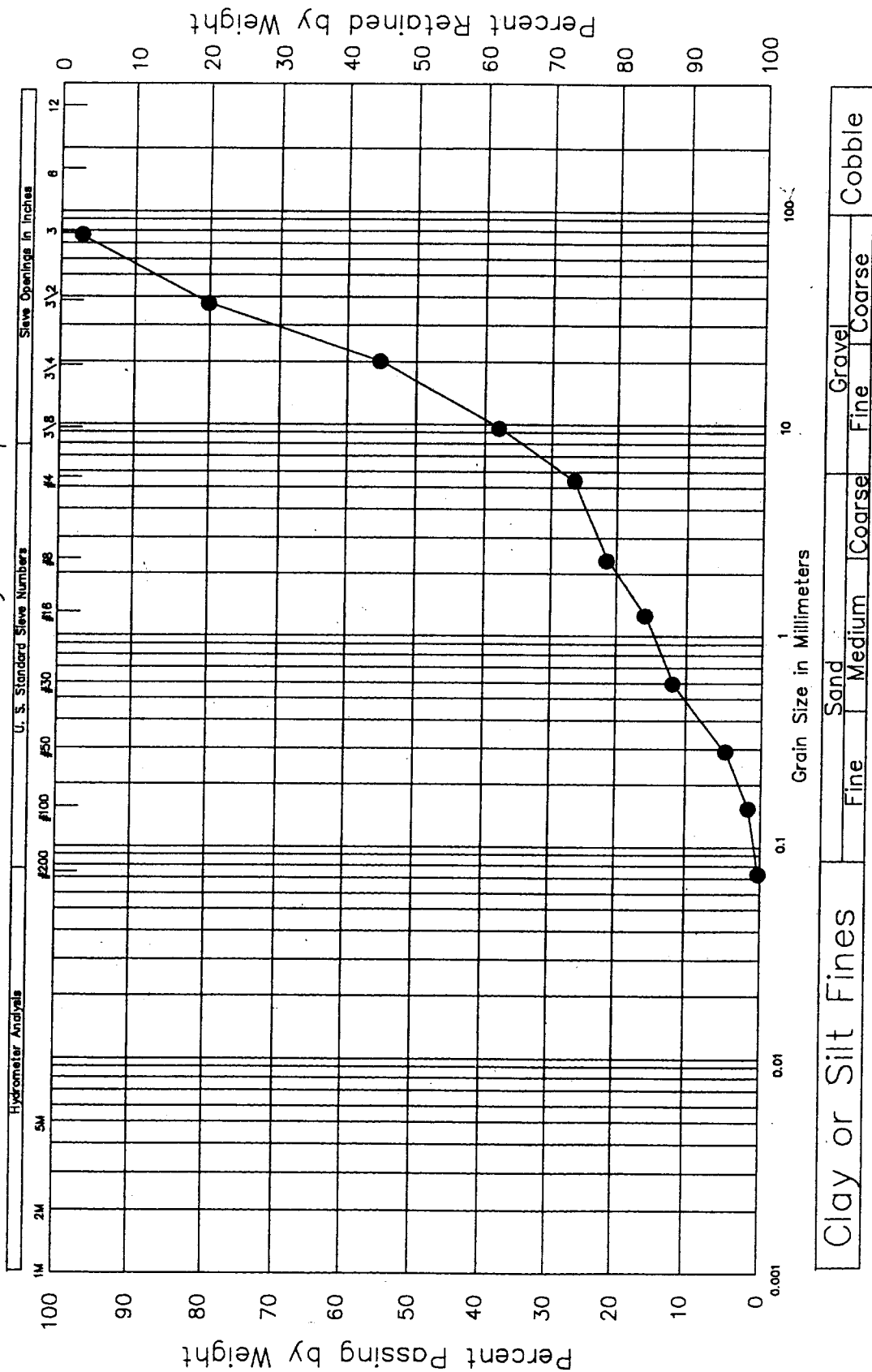
MECHANICAL ANALYSIS OF THE  
PALISADES EROSION SITE

# Mechanical Analysis Graph



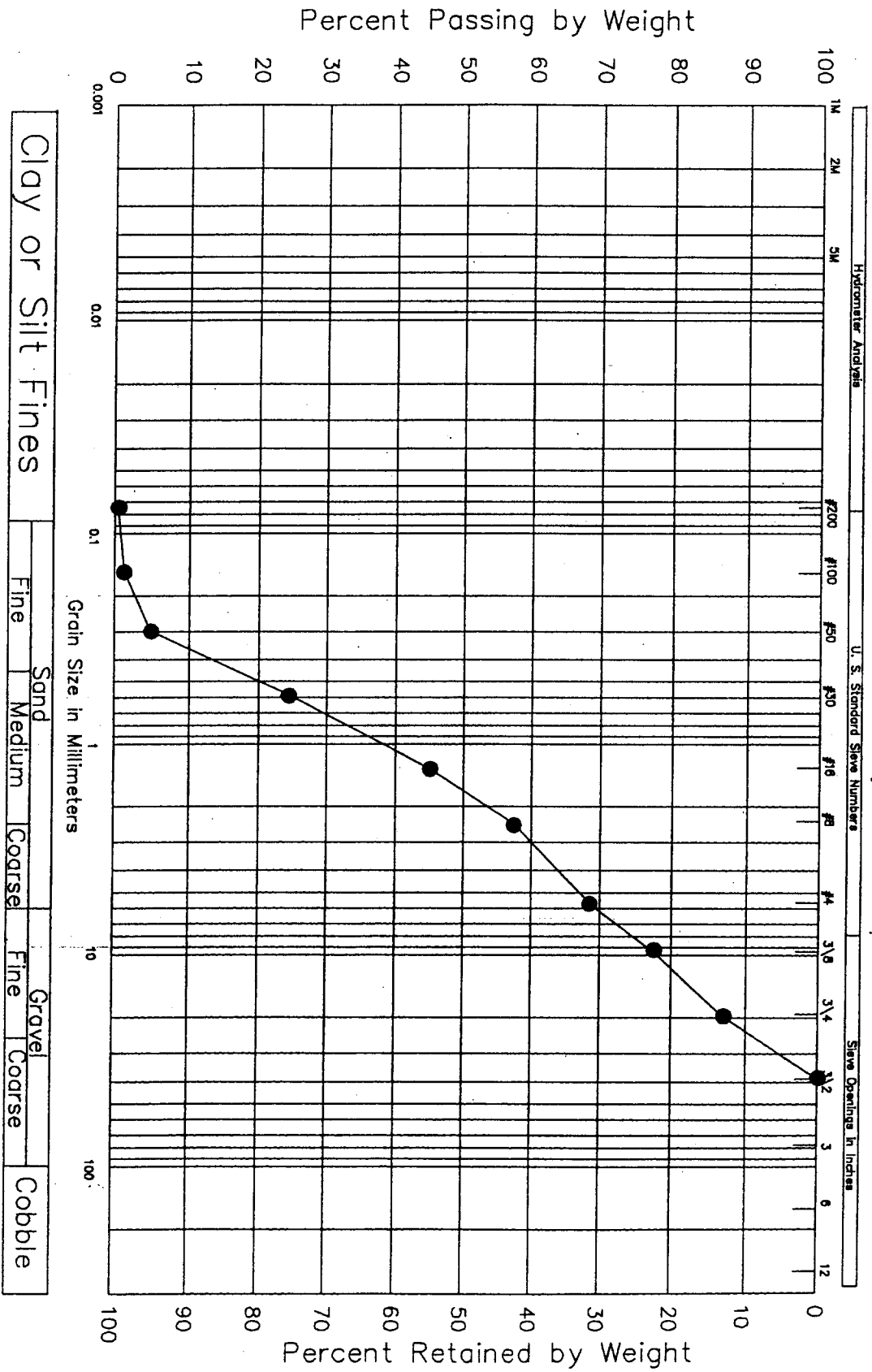
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BIG CHICO CREEK EROSION SITE

# Mechanical Analysis Graph



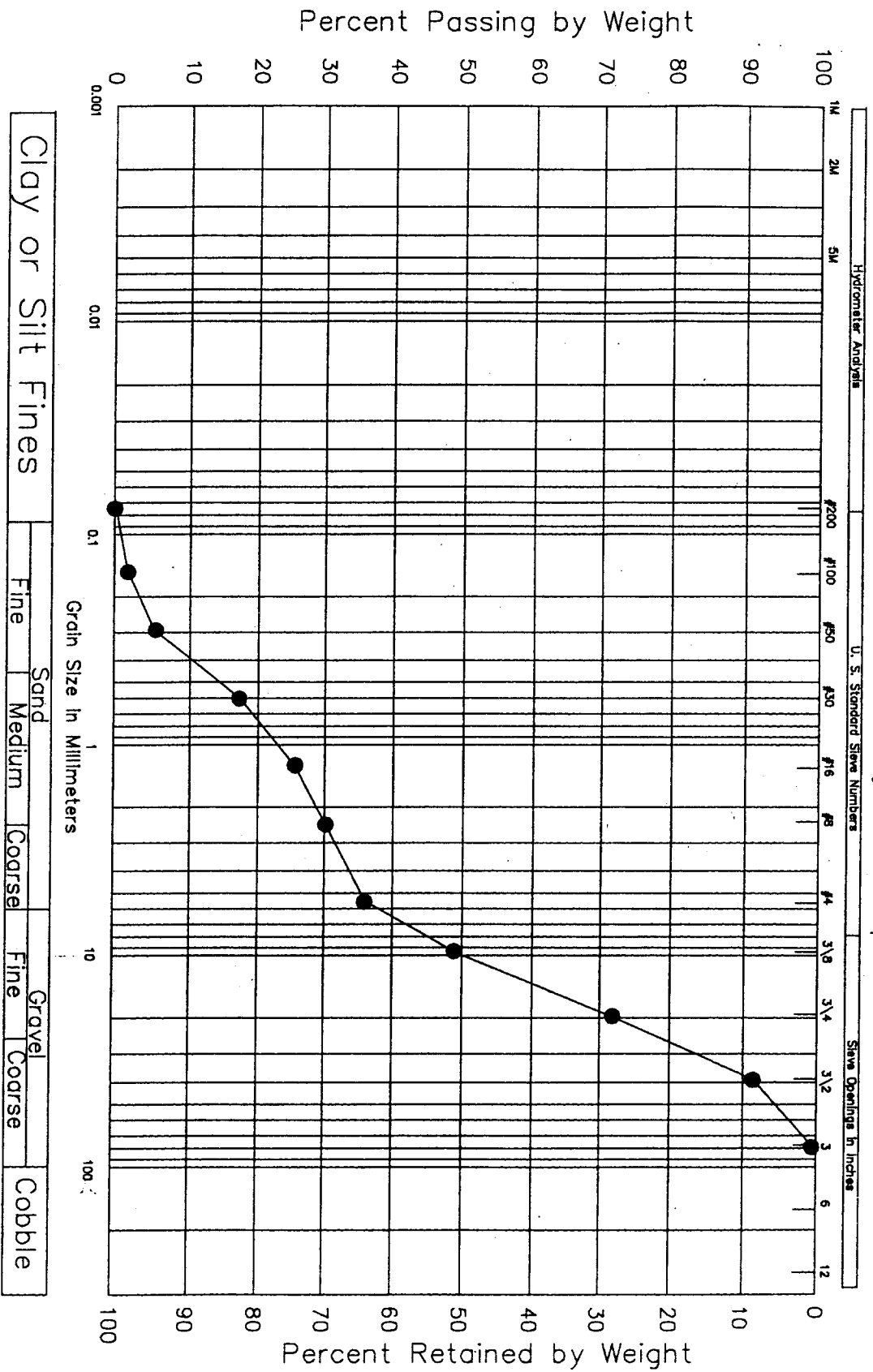
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RANCHO DE FARWELL EROSION SITE

# Mechanical Analysis Graph



MECHANICAL ANALYSIS OF THE  
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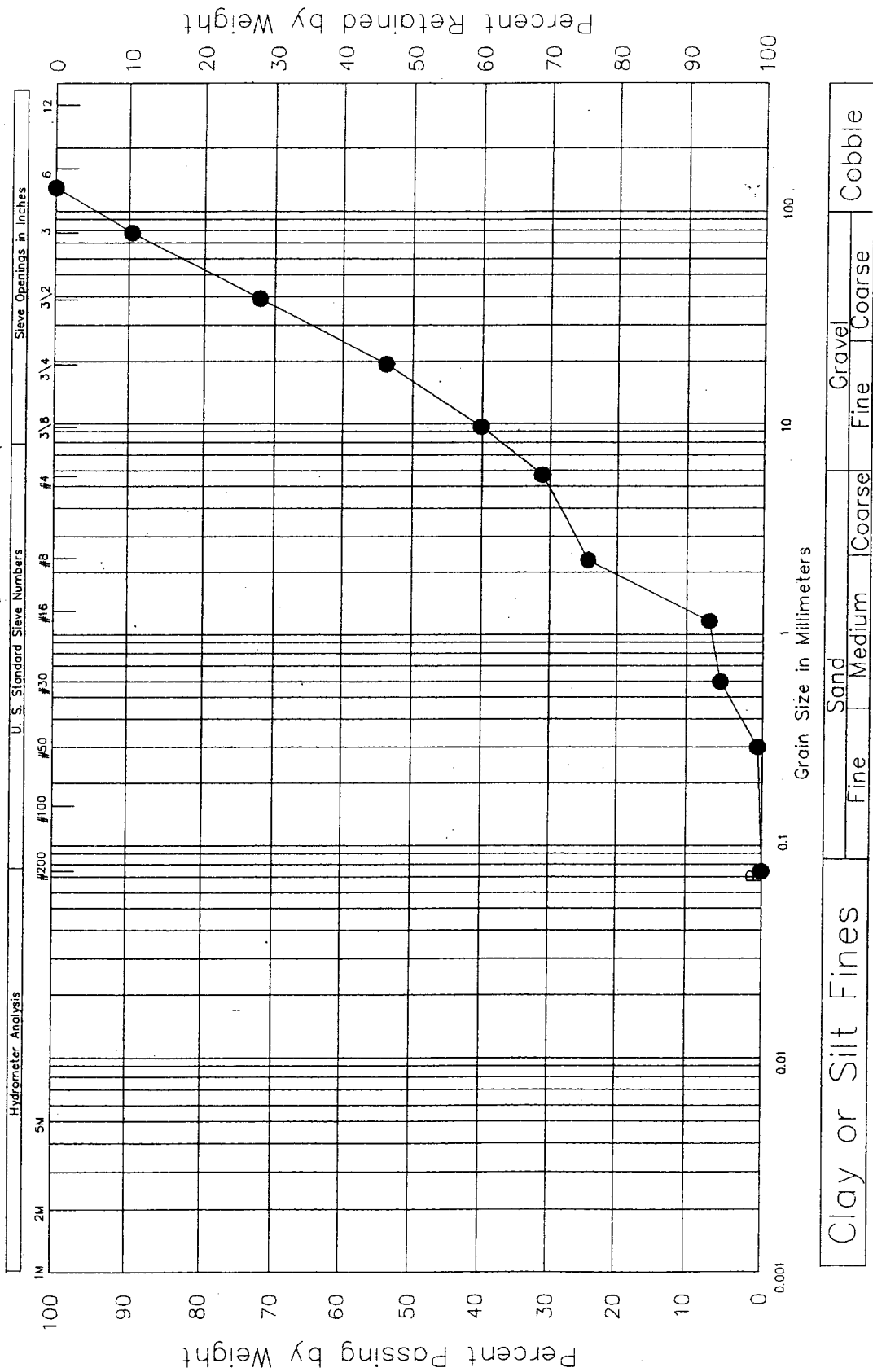
# Mechanical Analysis Graph



MECHANICAL ANALYSIS OF THE  
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# Mechanical Analysis Graph

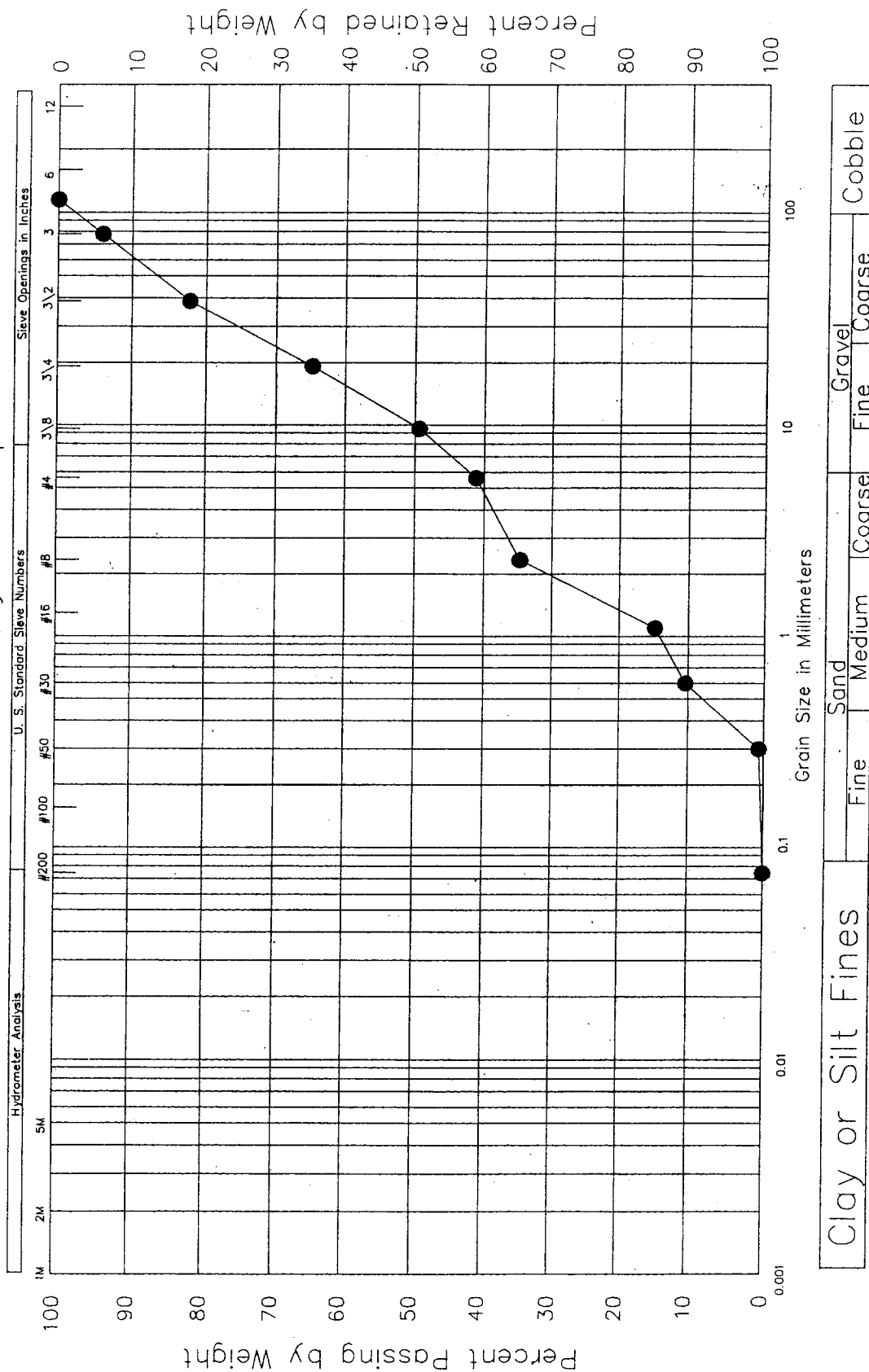


MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT01

[illegible]

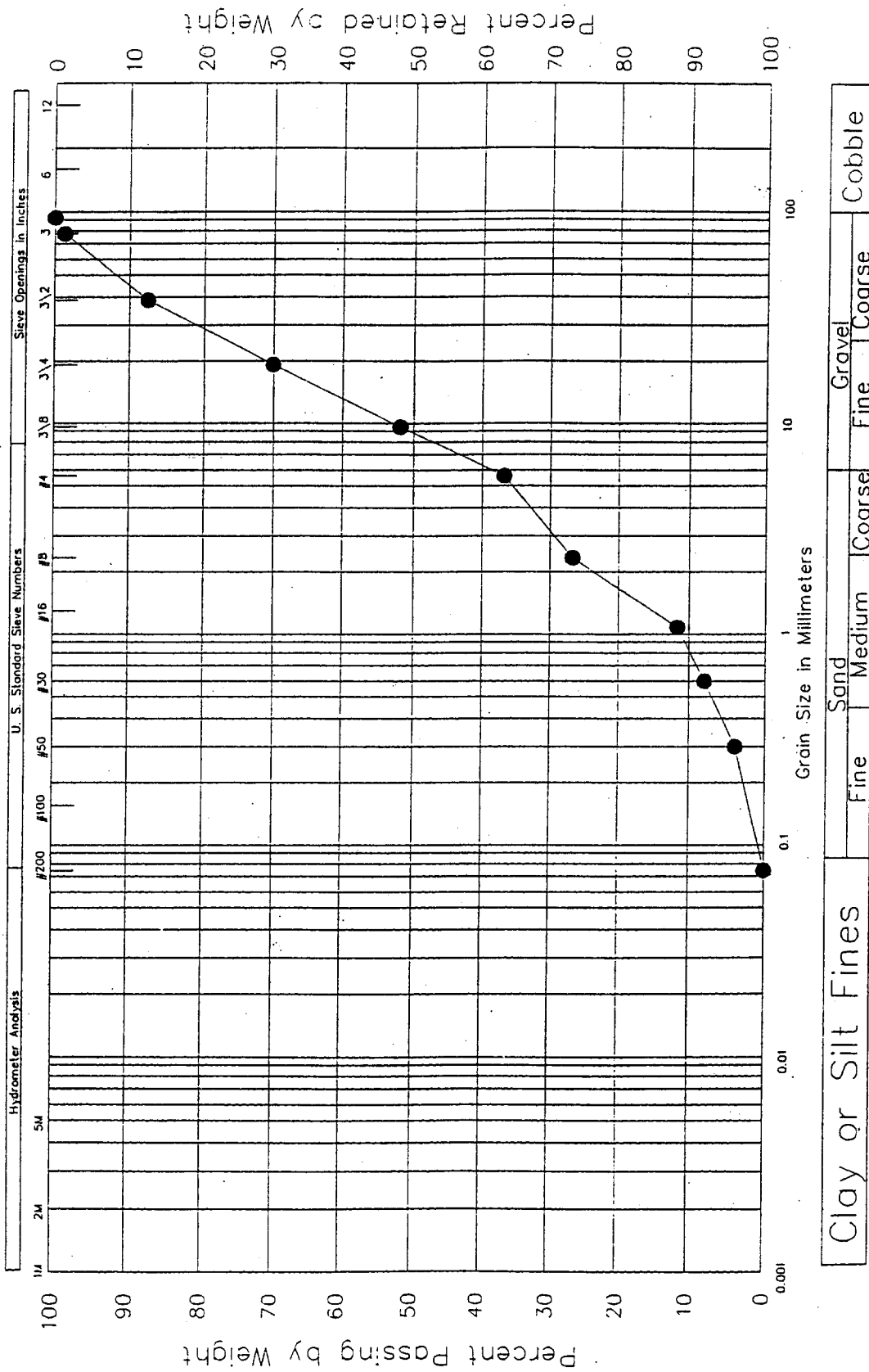
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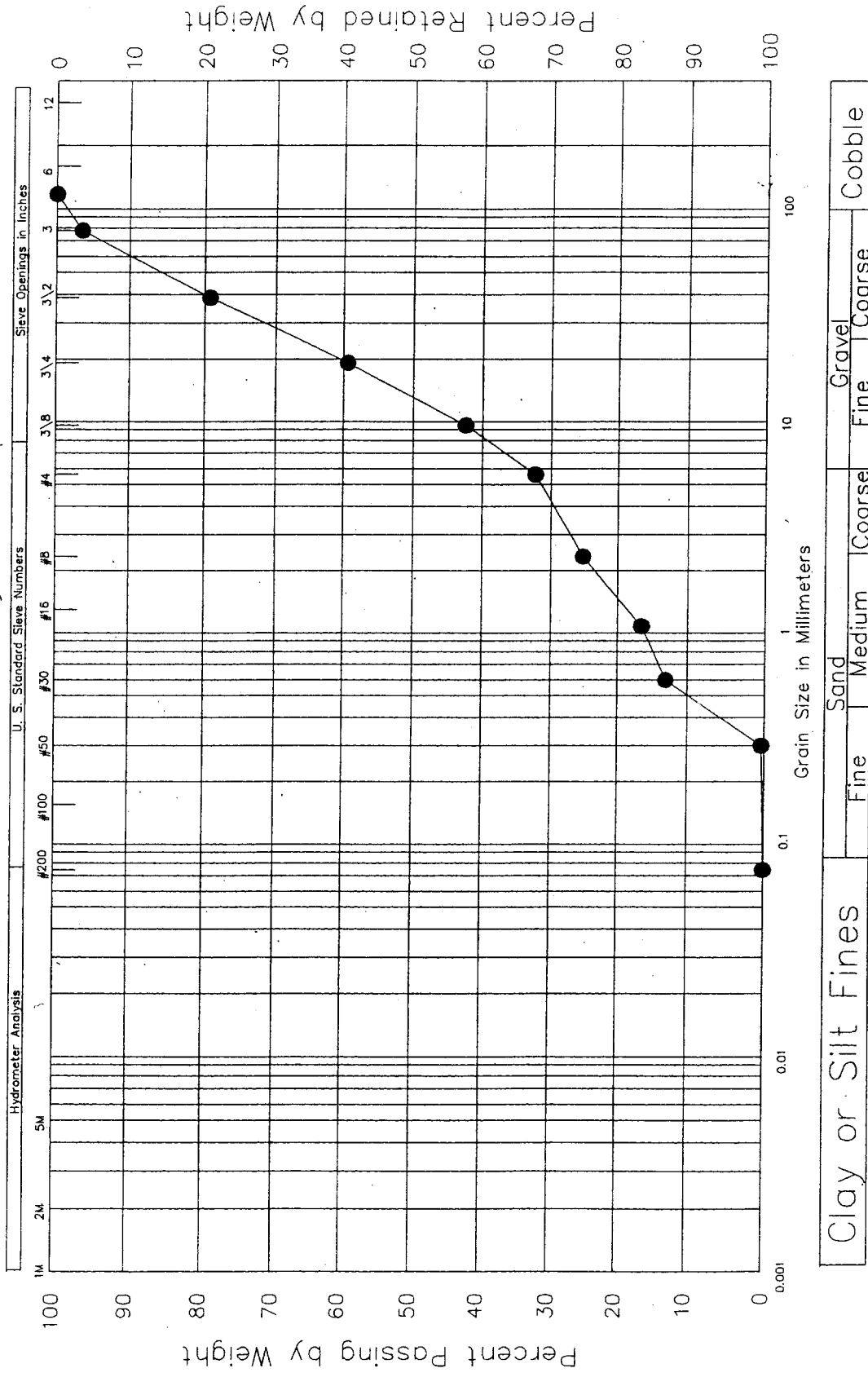
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT03

# Mechanical Analysis Graph



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT04

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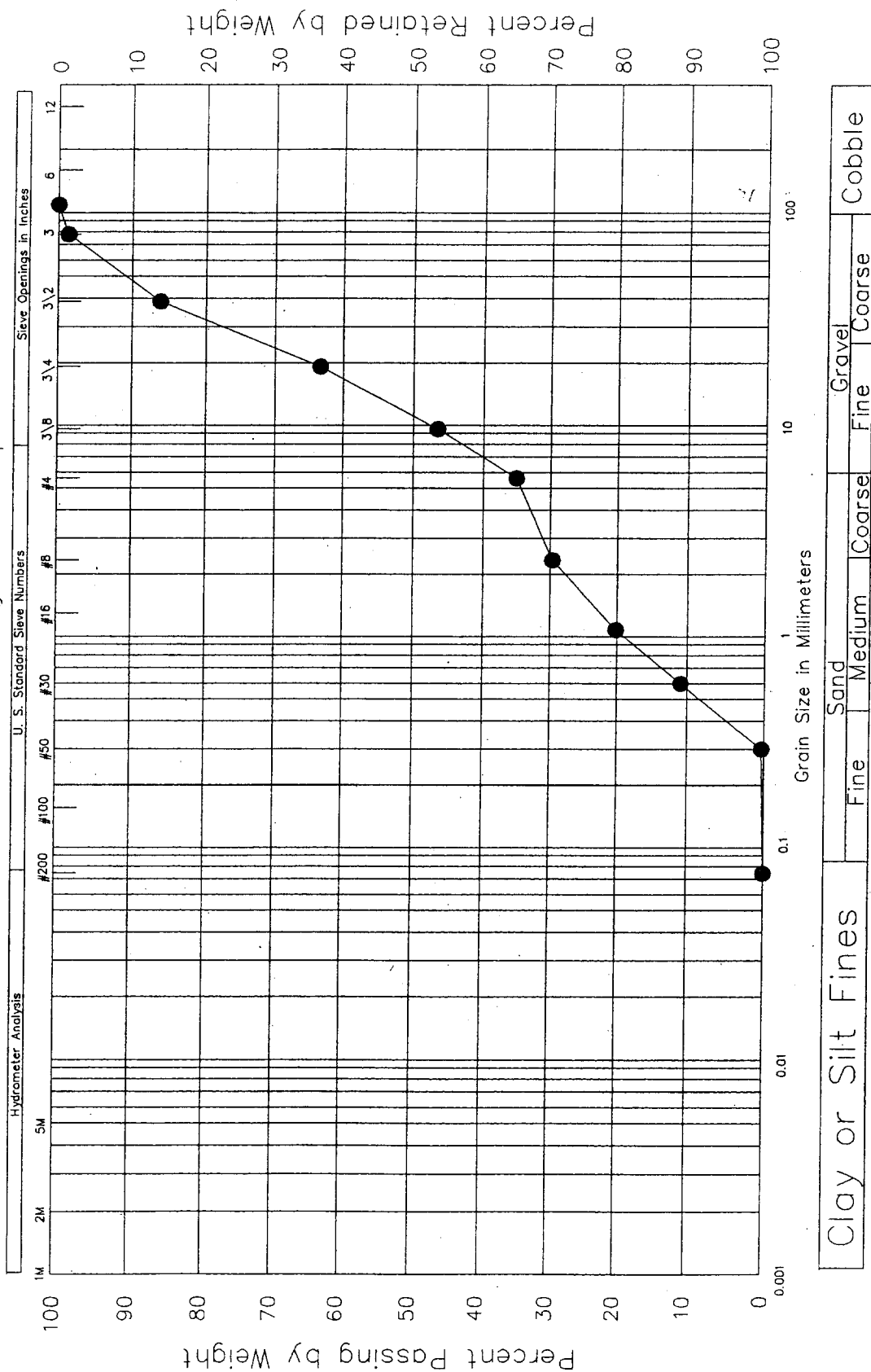


**Grain Size Analysis Data**

Grain Size (mm)	Sieve Number	Percent Passing (%)	Percent Retained (%)
0.075	#200	100	0
0.075	#200	0	100

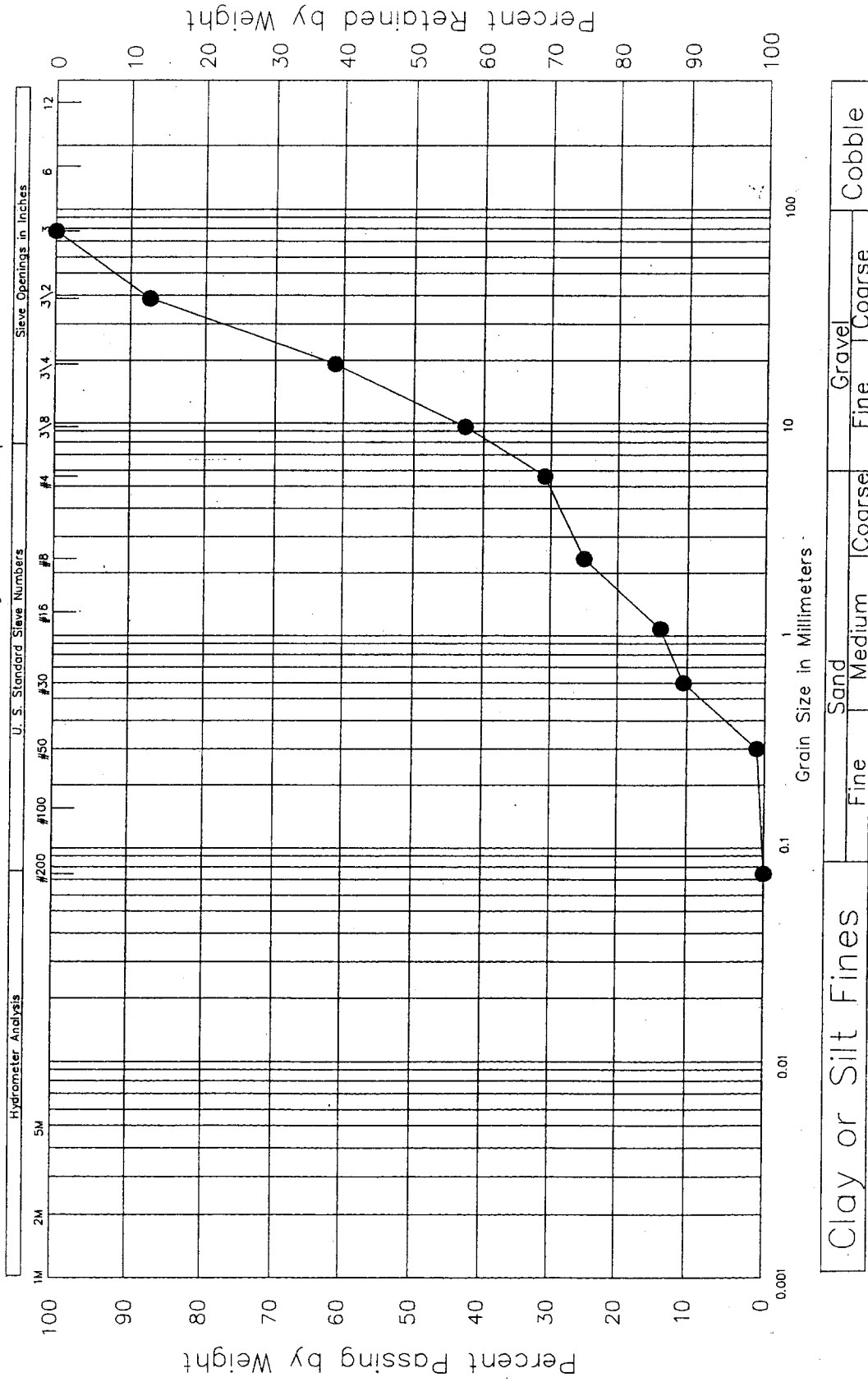
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT06

# Mechanical Analysis Graph



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT07

# Mechanical Analysis Graph



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER

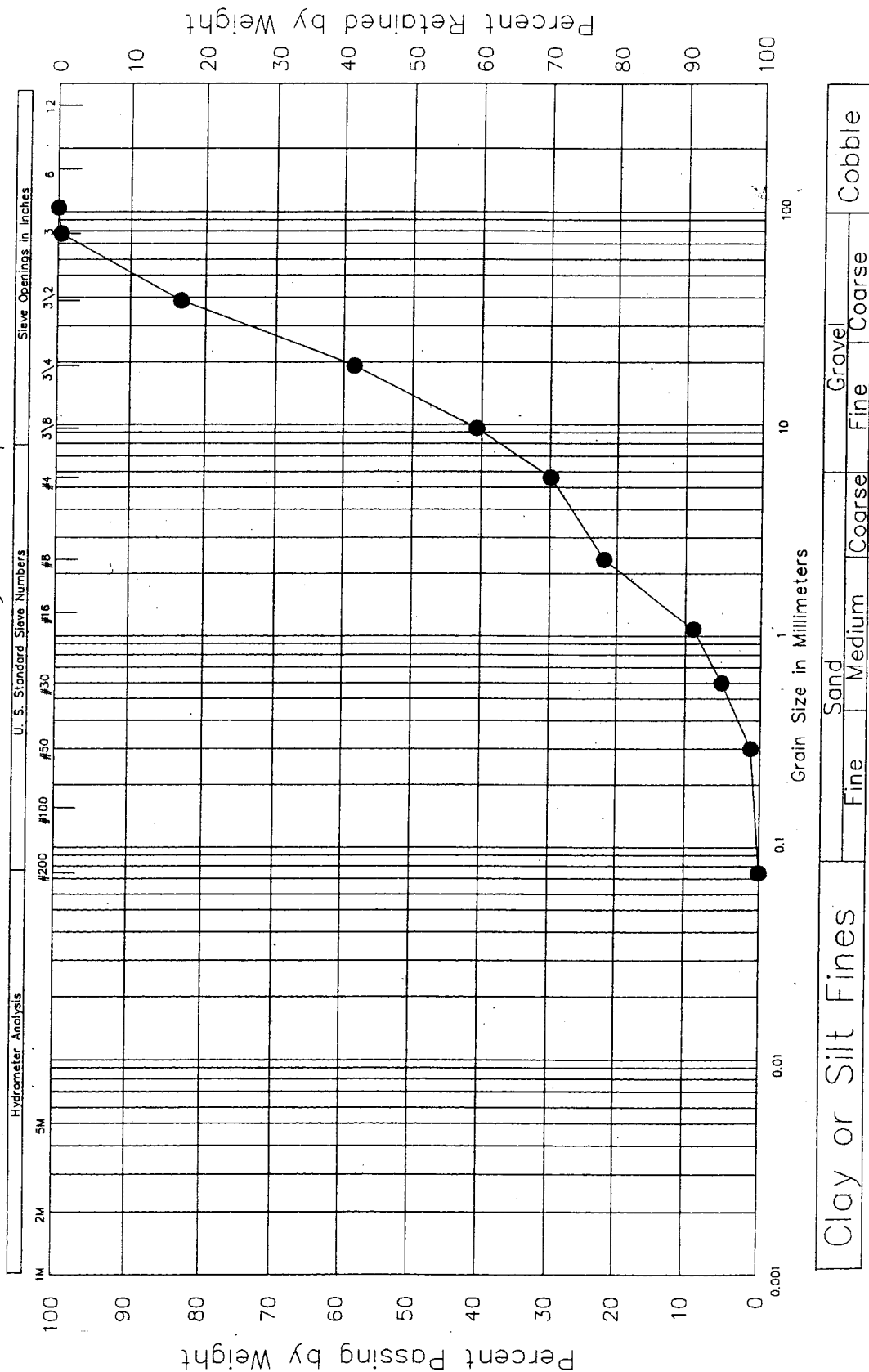
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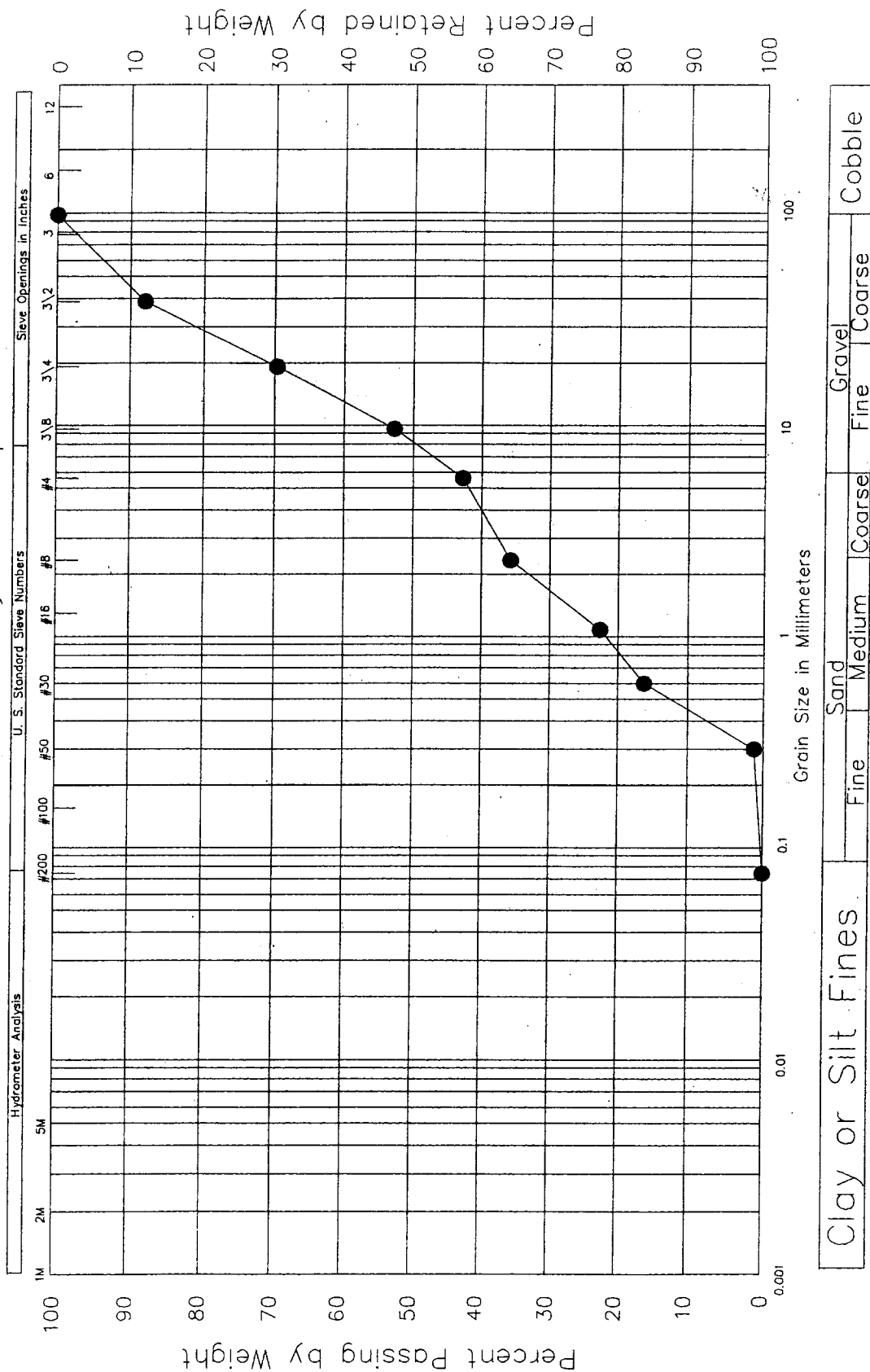
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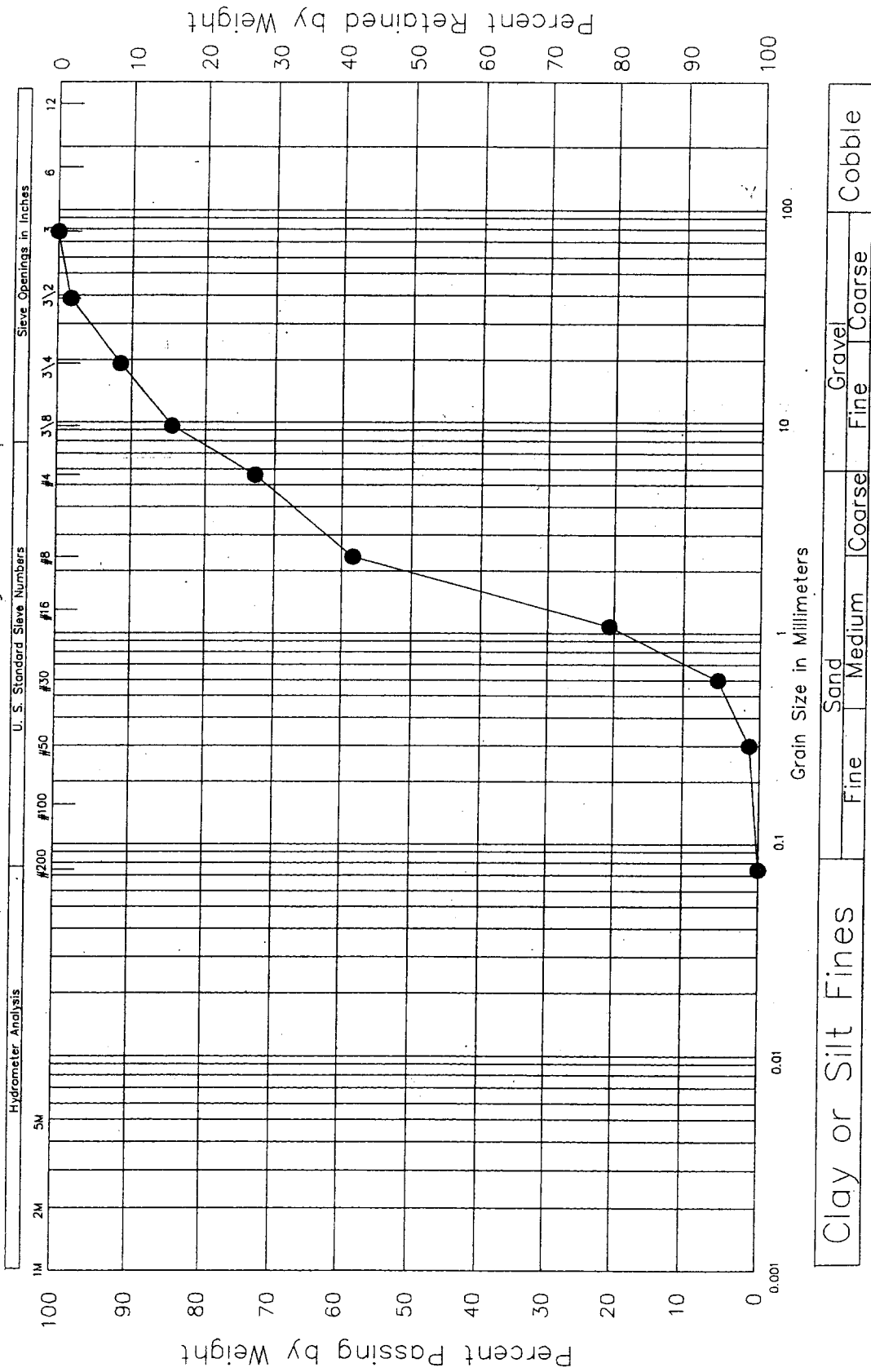
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SITE: SACT10

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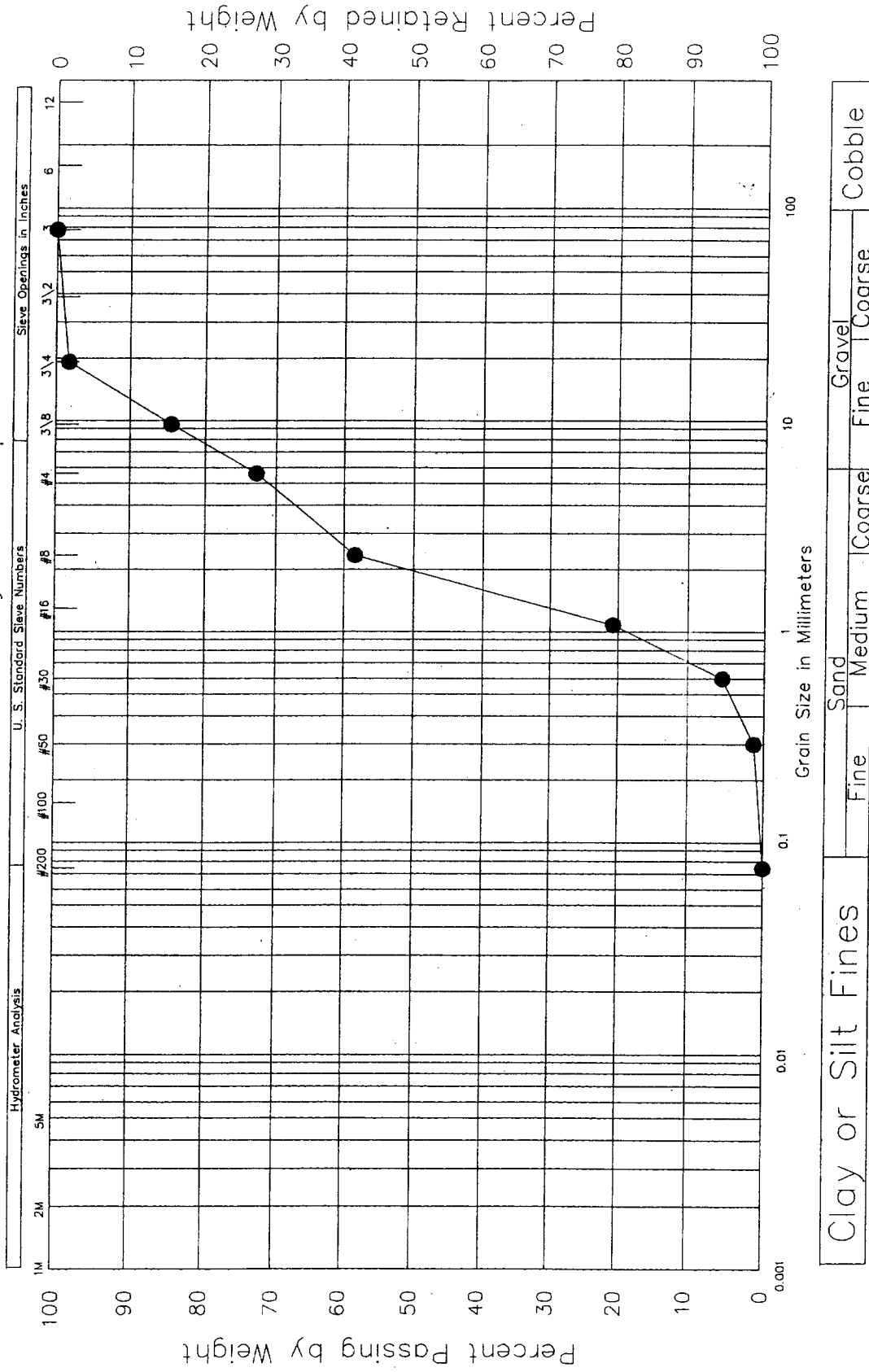
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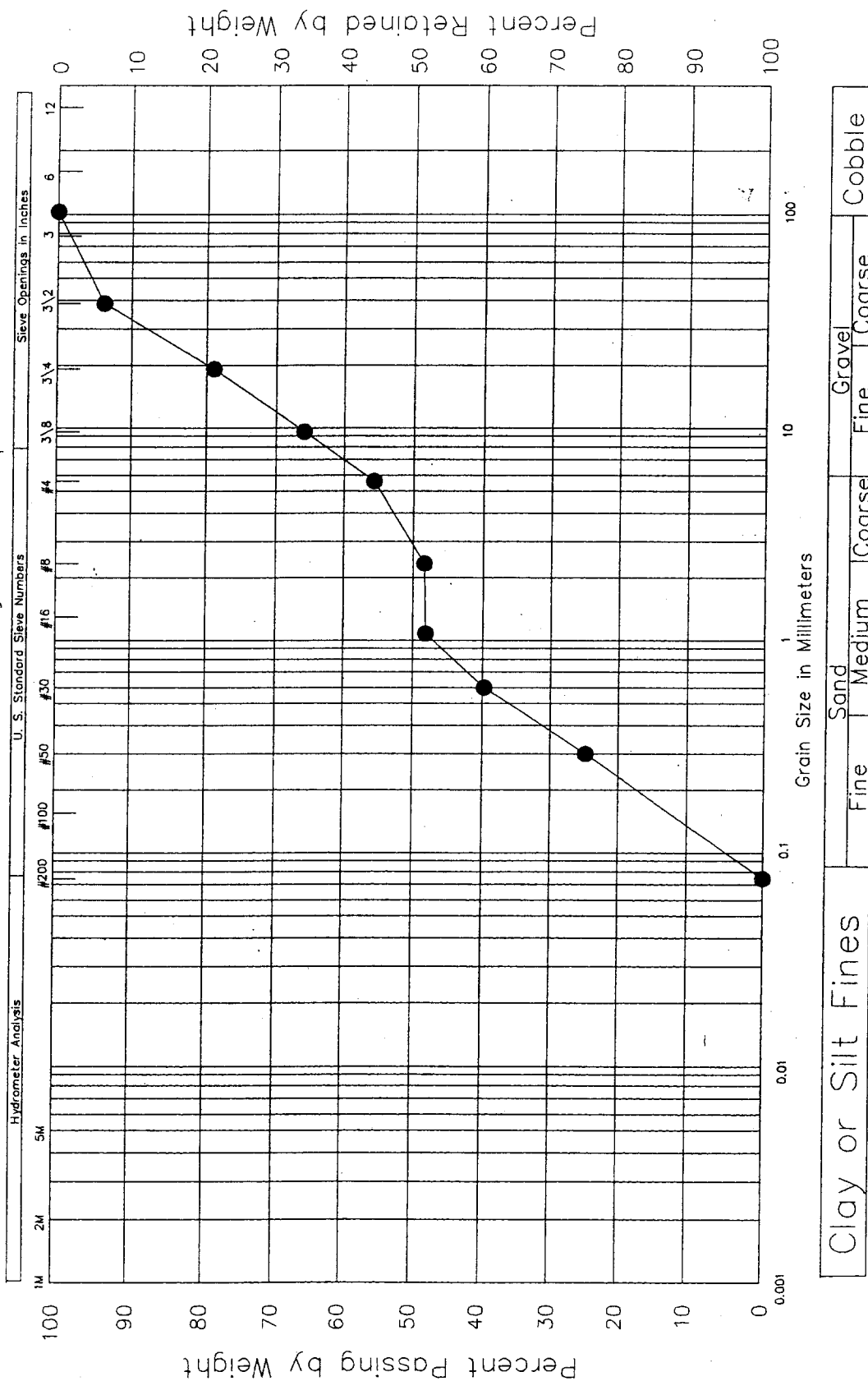


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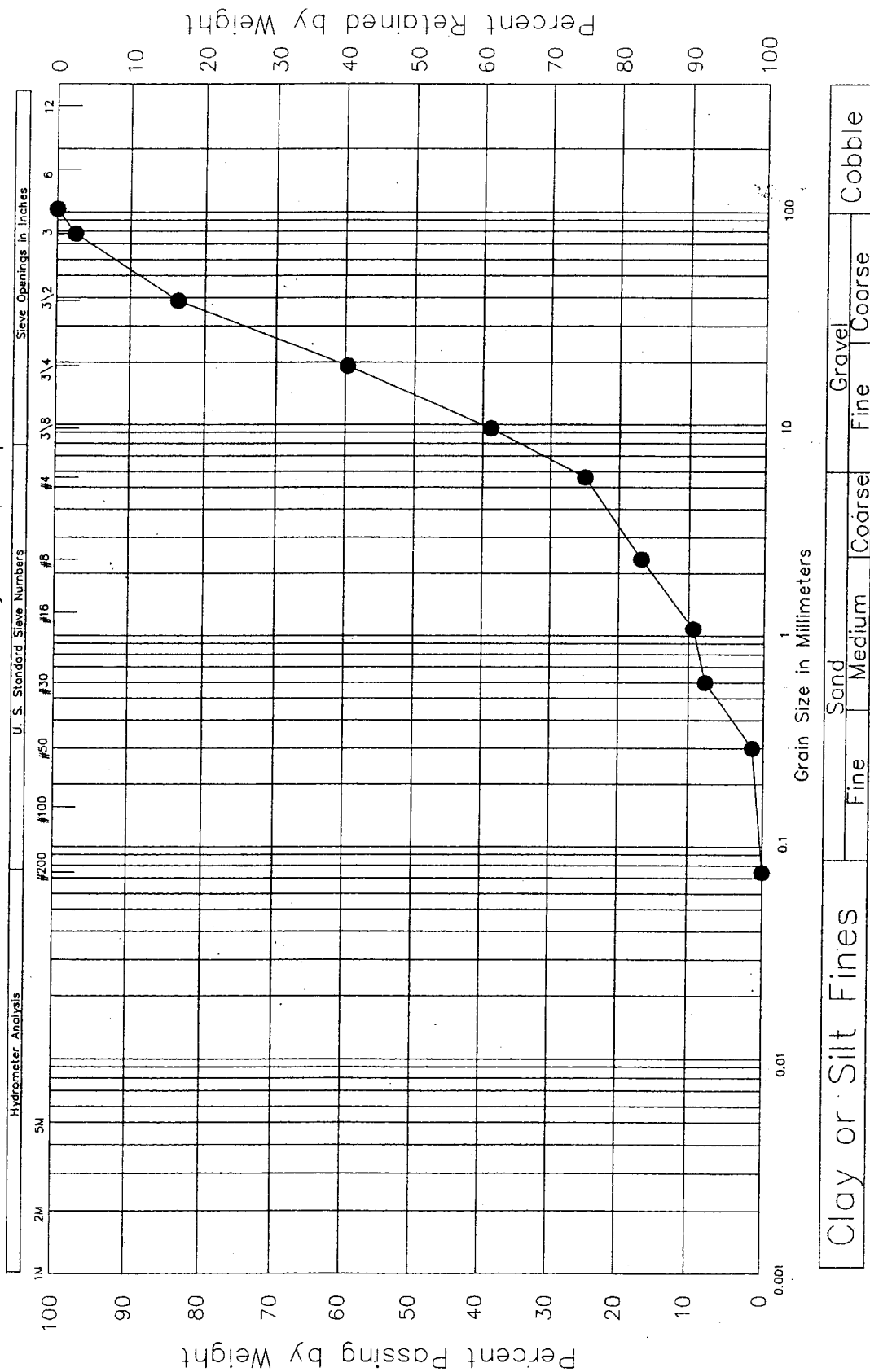


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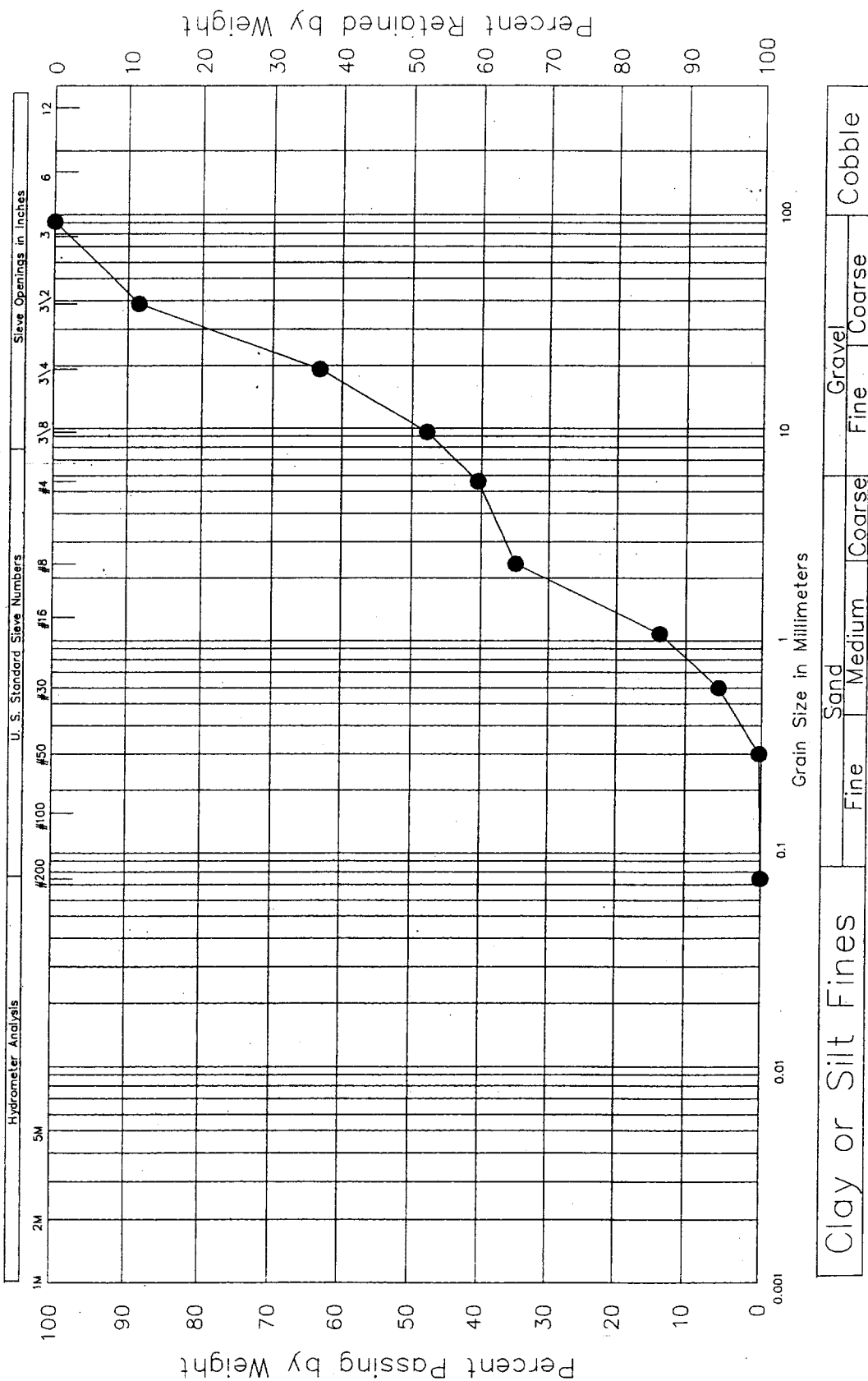
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SITE: SACT14

# Mechanical Analysis Graph



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
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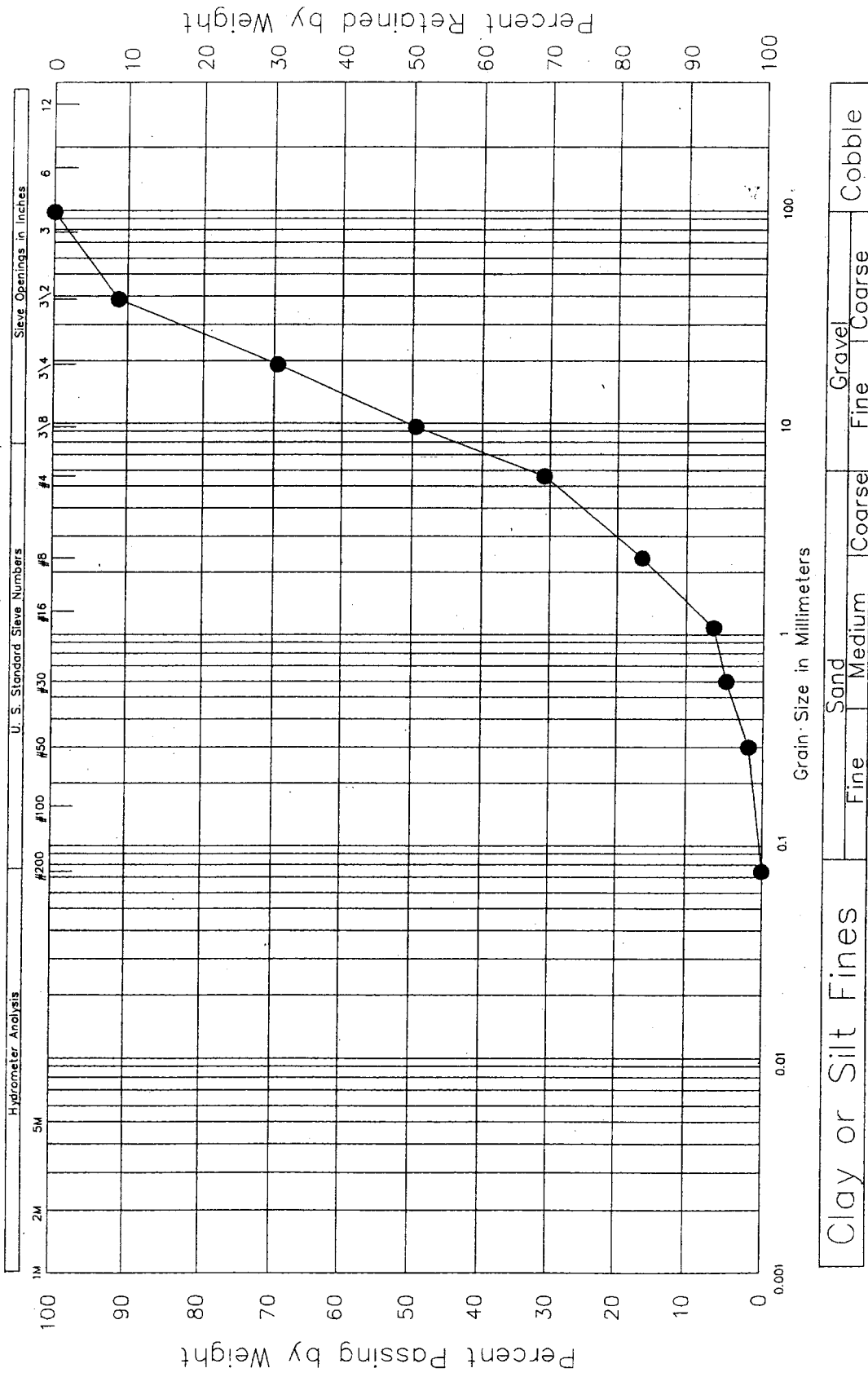
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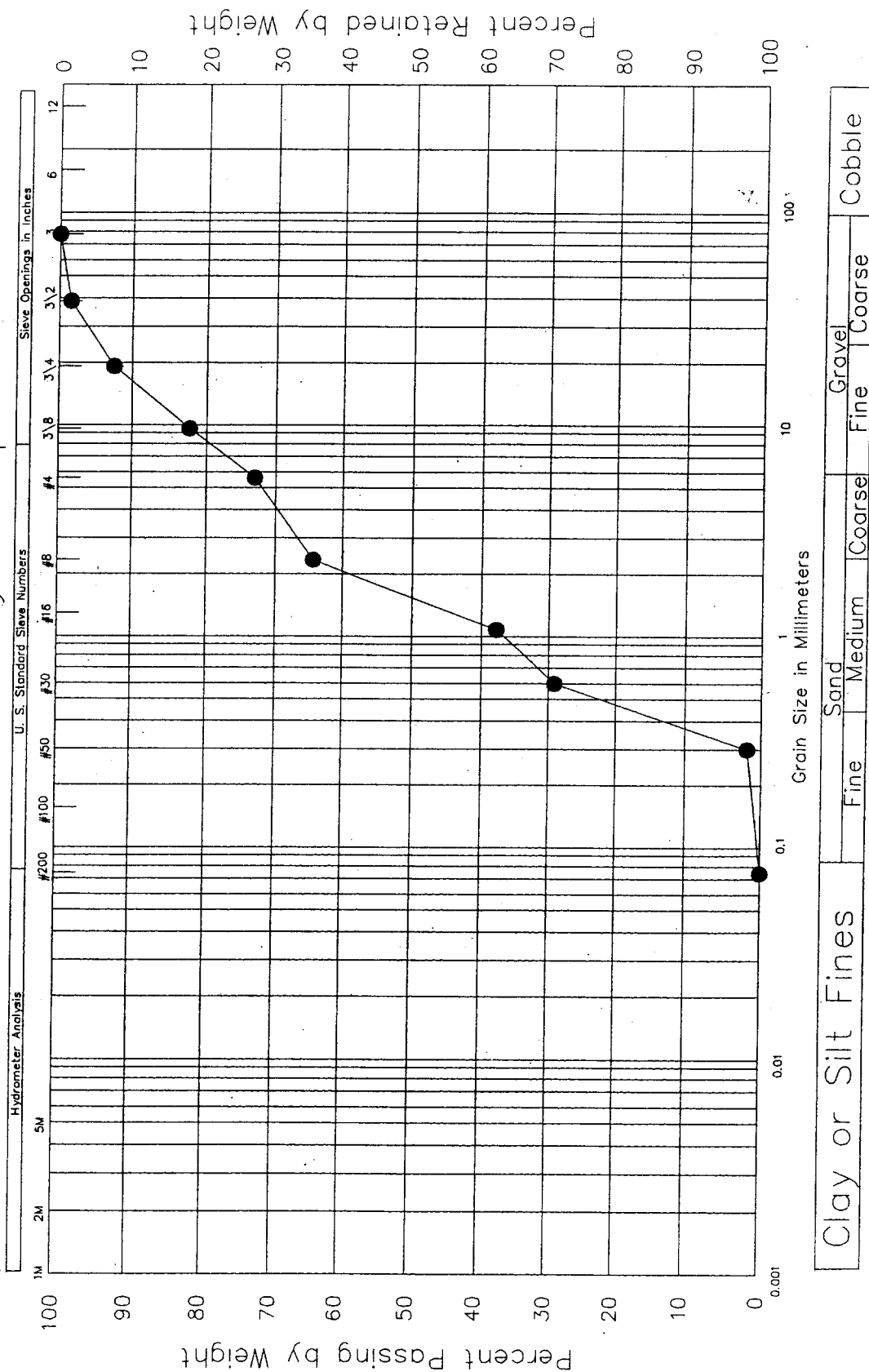
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SITE: SACT16



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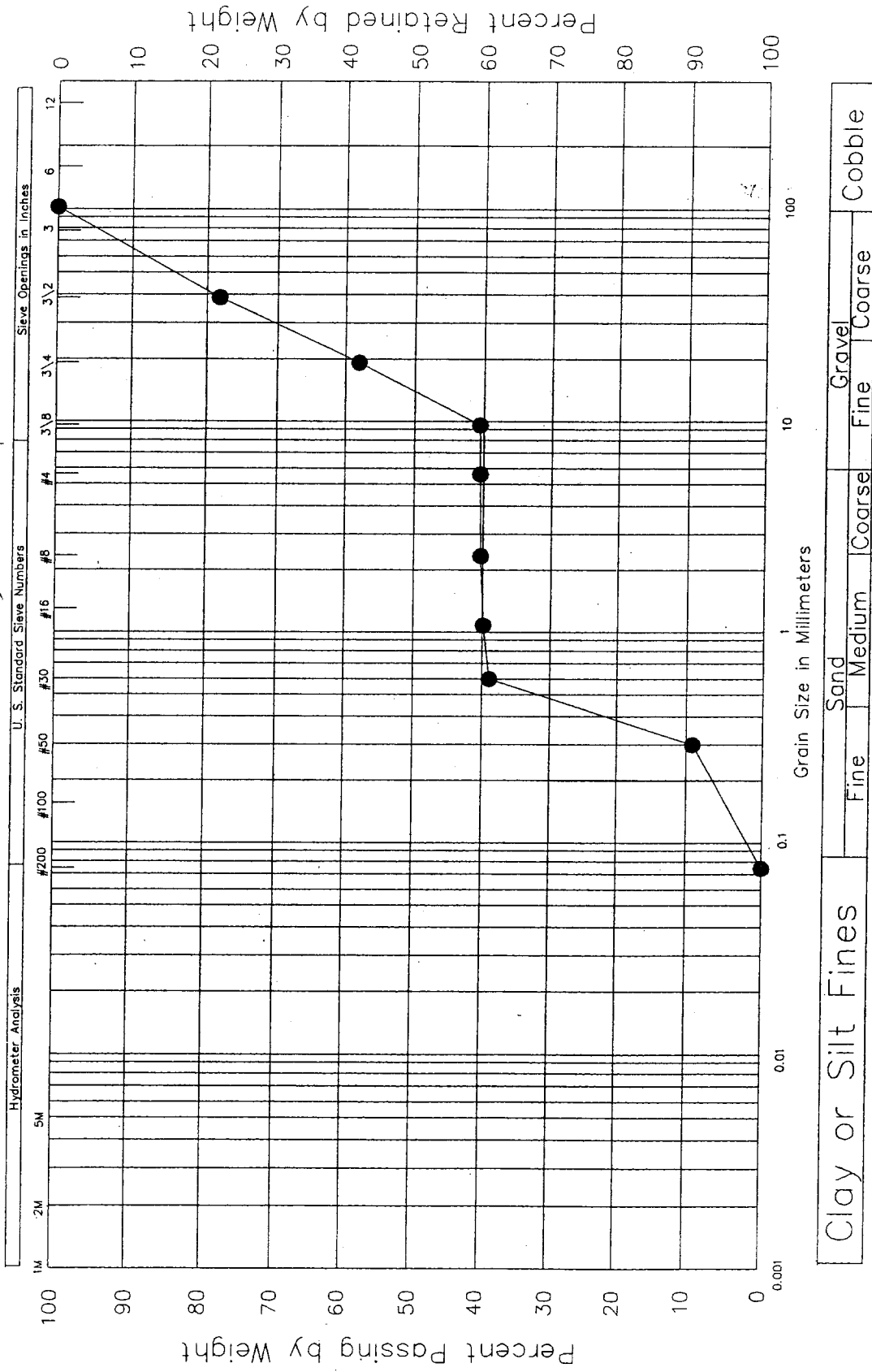


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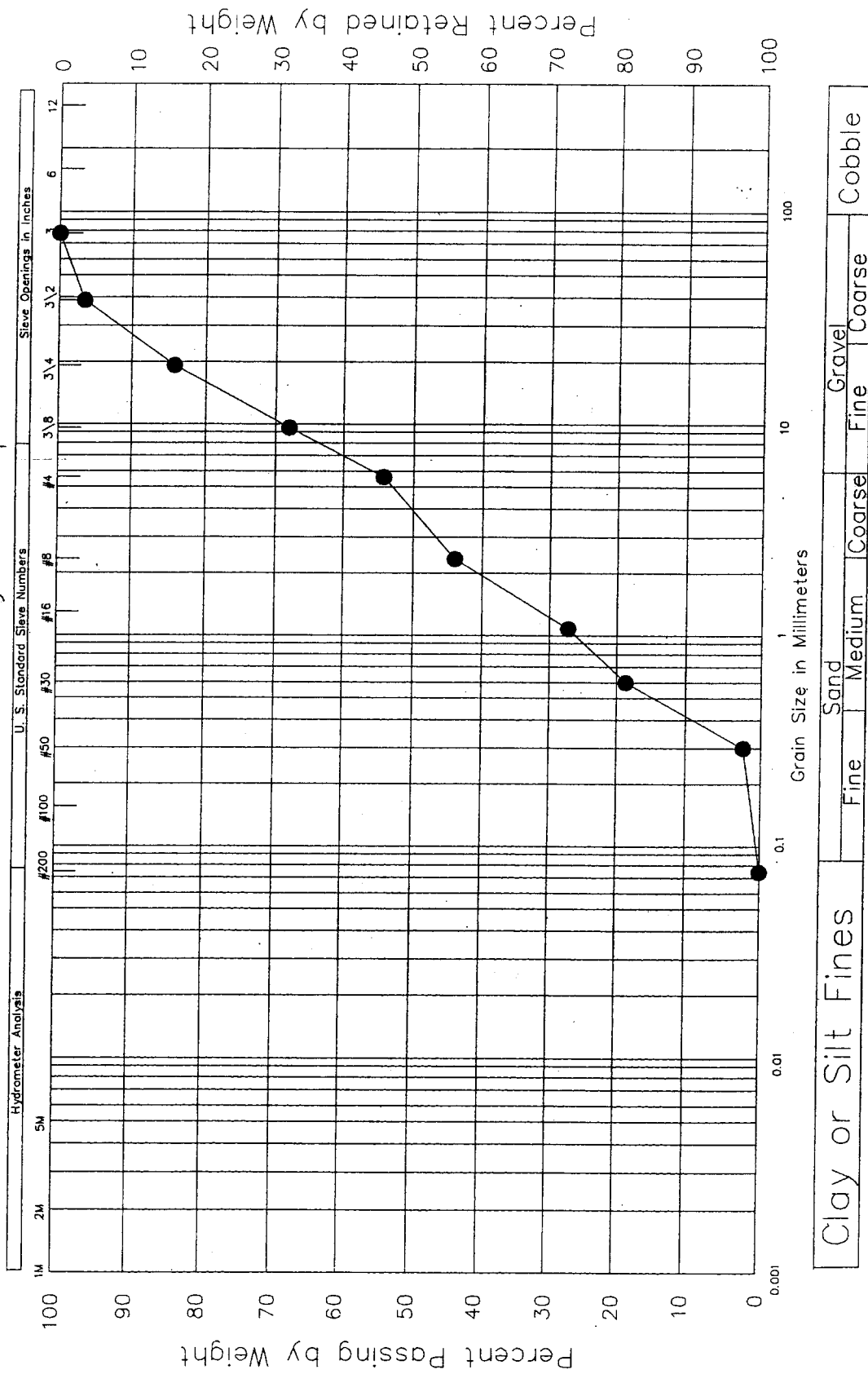
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SITE: SACT18

# Mechanical Analysis Graph



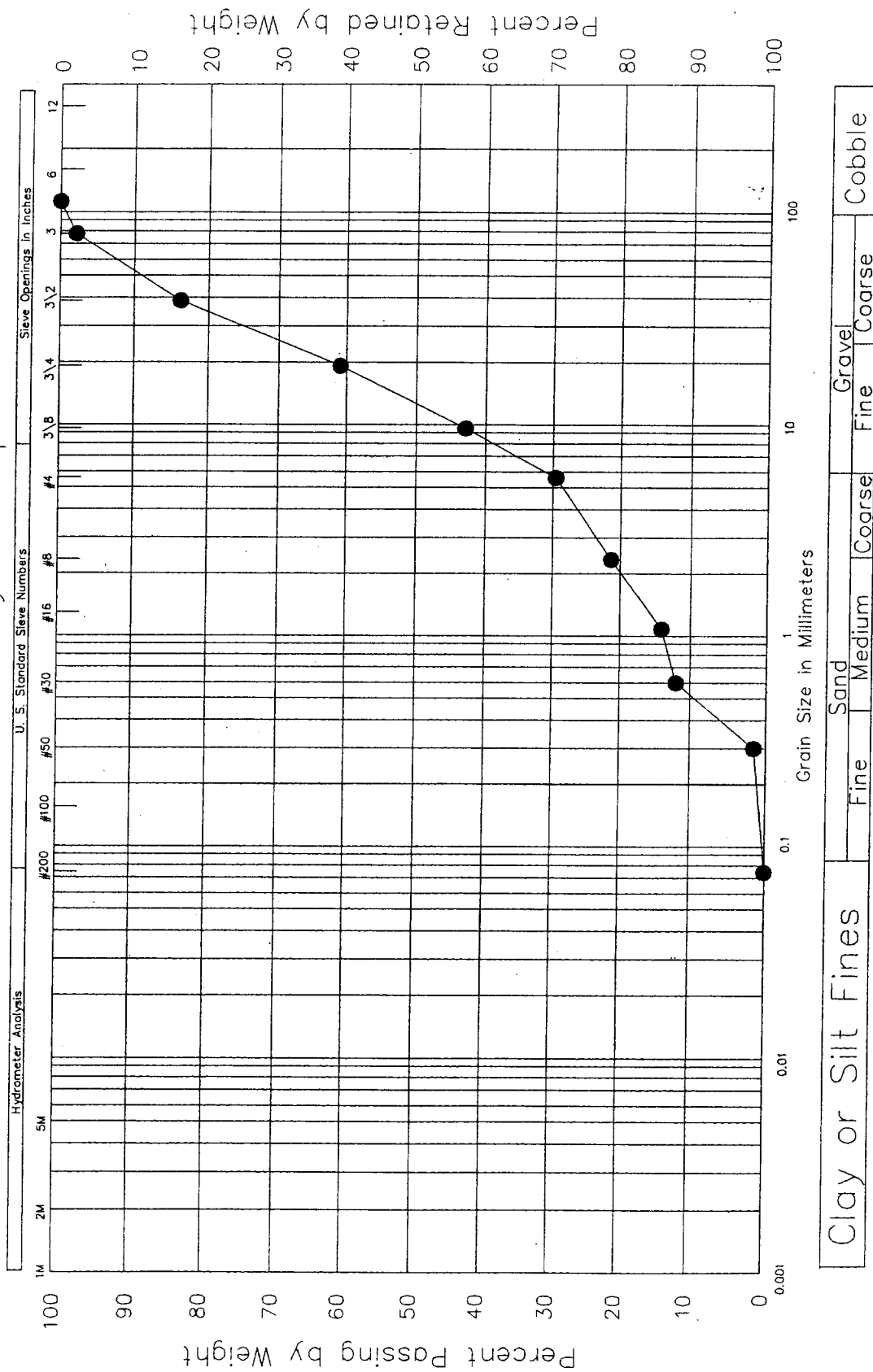
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SITE: SACT19

# Mechanical Analysis Graph

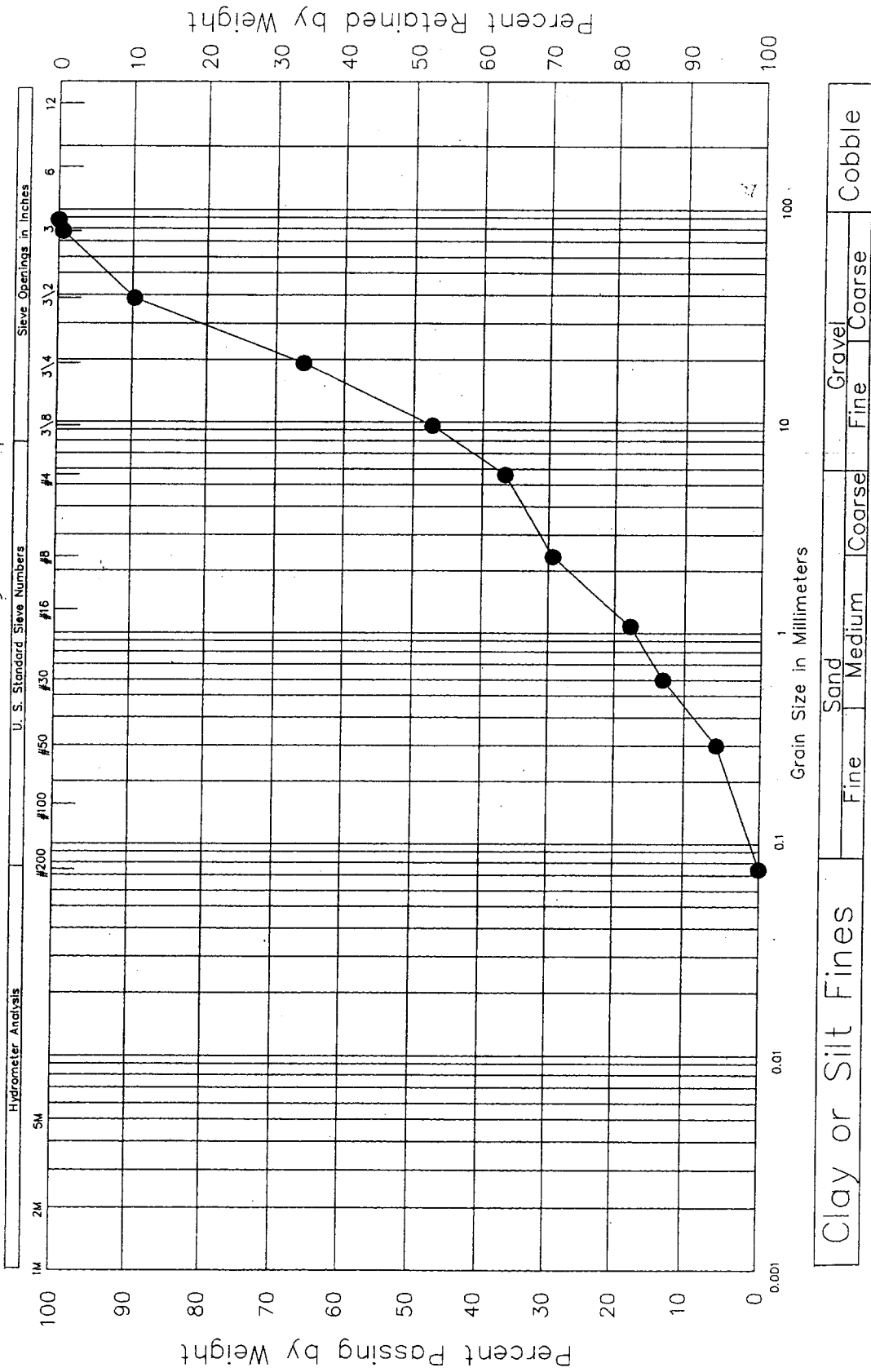


MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT20

# Mechanical Analysis Graph



# Mechanical Analysis Graph

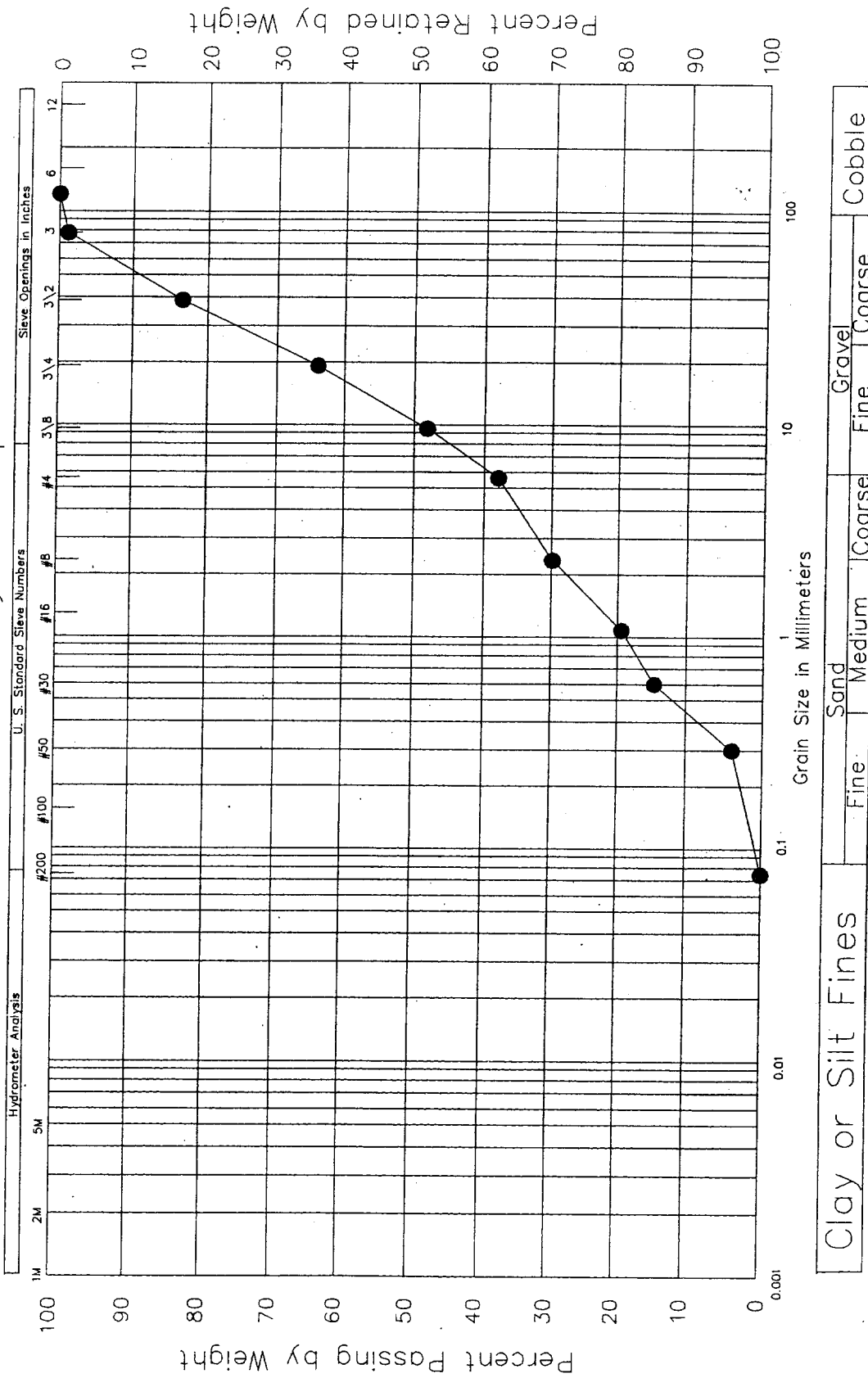


Grain Size (mm)	Percent Passing (%)
0.075	100
0.15	100
0.3	100
0.6	100
1.18	100
2.5	100
4.75	100
7.5	100
15	100
30	100
60	100
75	100
106	100
200	100
425	100
750	100
1060	100
2000	100
4750	100
7500	100
10600	100
20000	100
47500	100
75000	100
106000	100
200000	100
475000	100
750000	100
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# MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER

SITE: SACT23

# Mechanical Analysis Graph



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT24

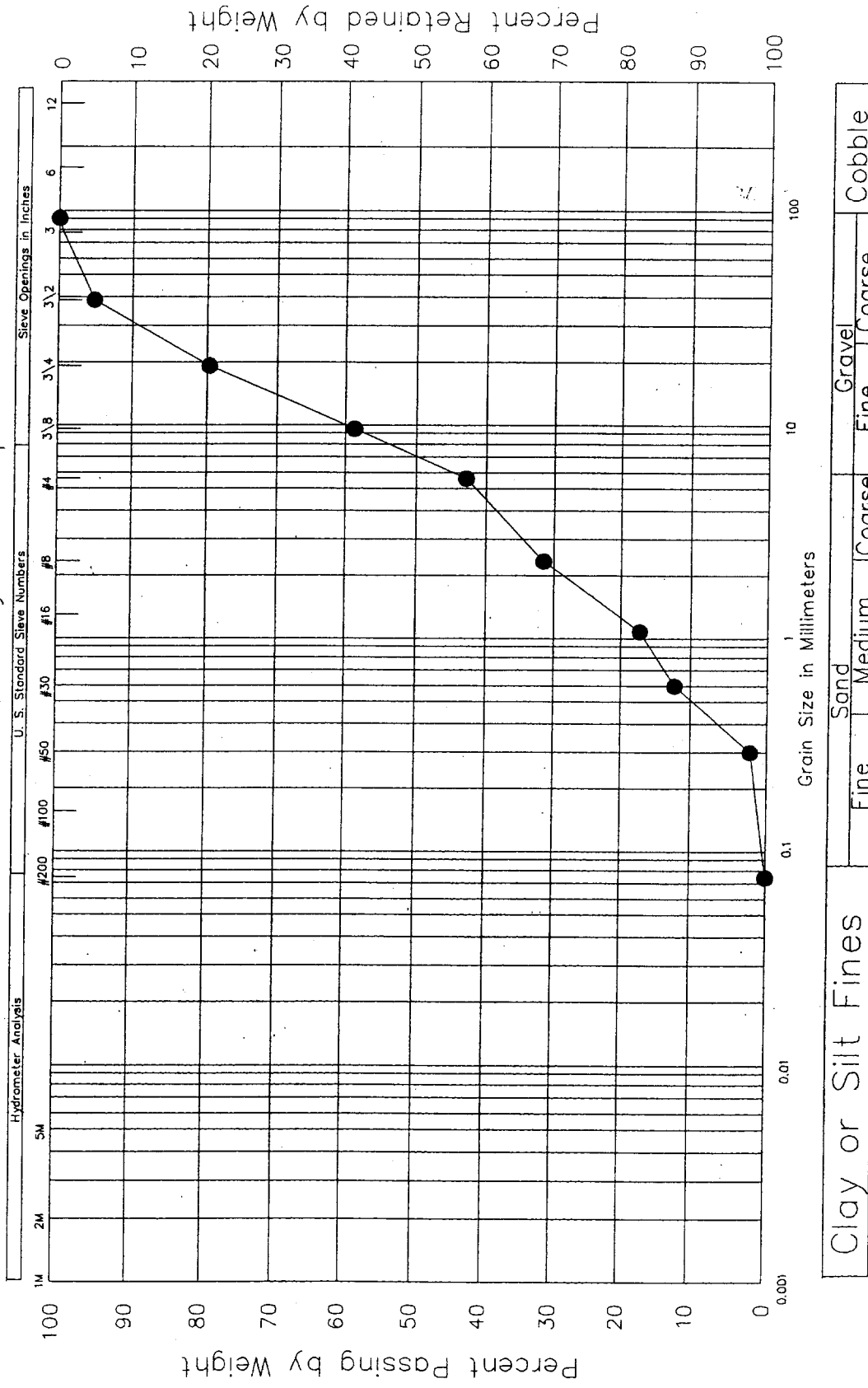


Grain Size (mm)	Percent Passing (%)
0.075	100
0.15	100
0.3	100
0.6	100
1.18	100
2.5	100
4.75	100
7.5	100
15	100
30	100
60	100
75	100

# MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER

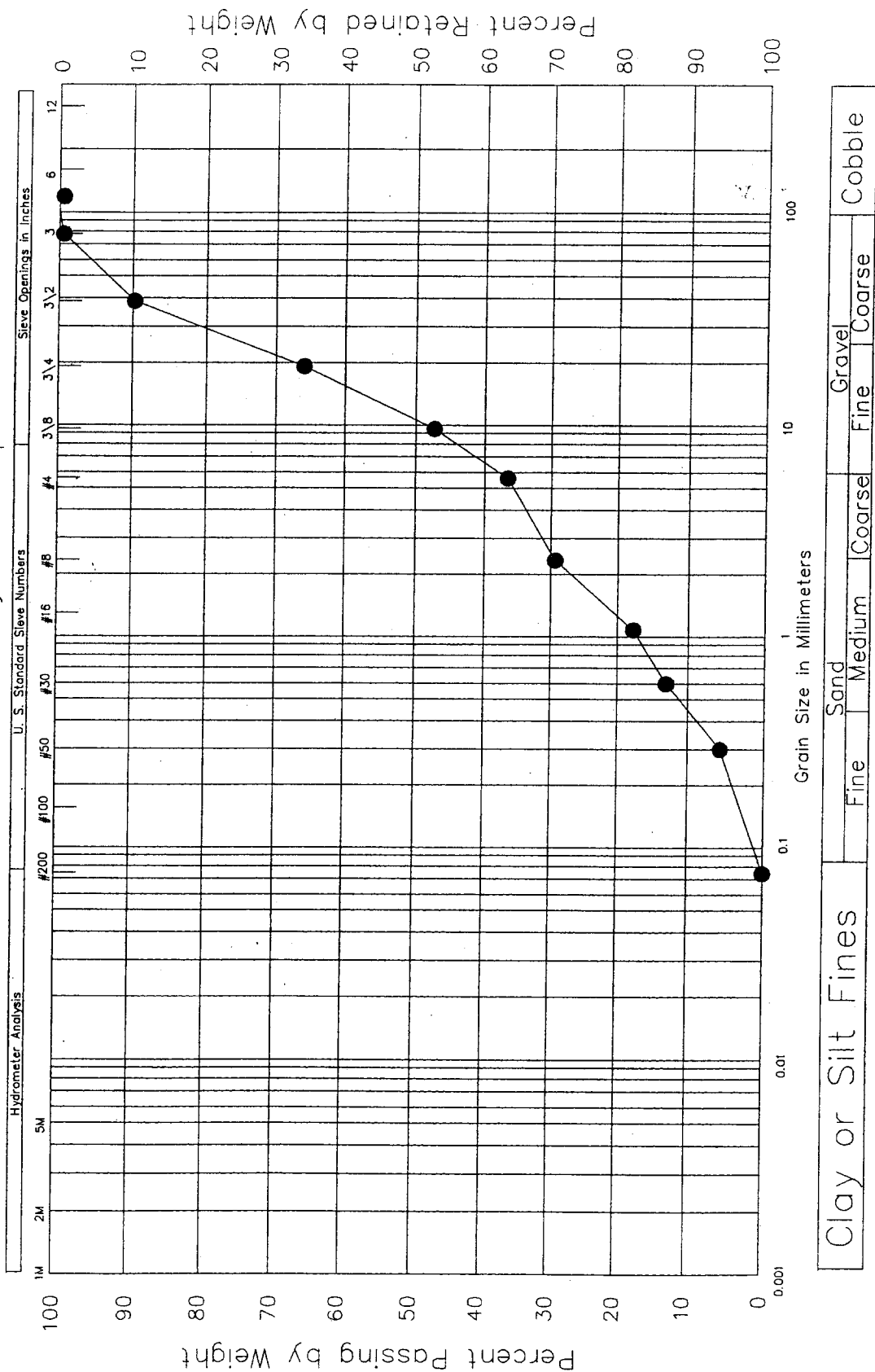
SITE: SACT25

# Mechanical Analysis Graph

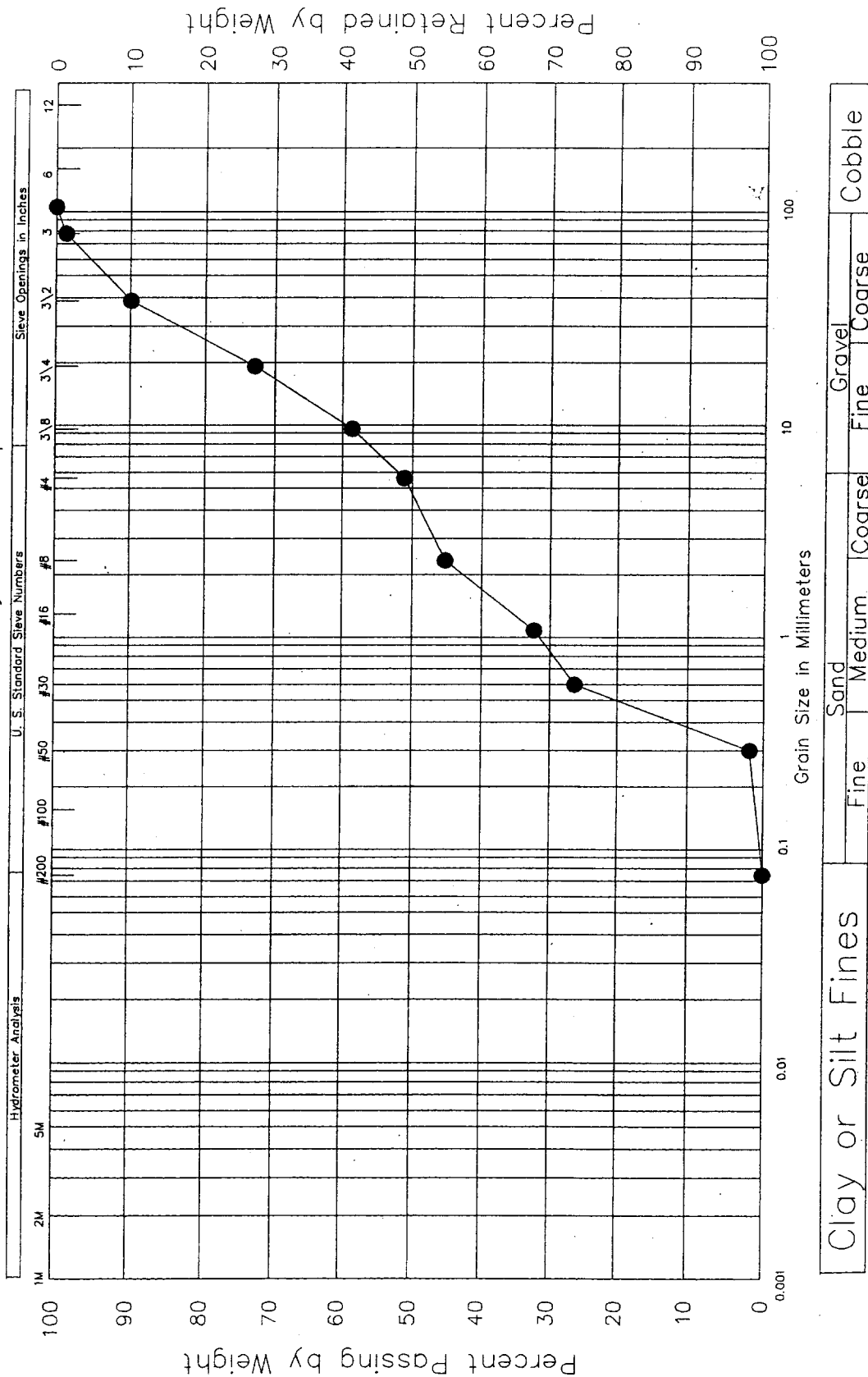


MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT26

# Mechanical Analysis Graph



# Mechanical Analysis Graph



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT28

Hydrometer Analysis		U. S. Standard Sieve Numbers				Grain Size in Millimeters							
1M	5M	#200	#100	#50	#30	#16	#8	#4	3/8	3/4	3/2	6	12
100	90	80	70	60	50	40	30	20	10	0	0	0	0
0	10	20	30	40	50	60	70	80	90	100	100	100	100

Percent Passing by Weight

Percent Retained by Weight

Grain Size in Millimeters

Sieve Openings in Inches

Clay or Silt Fines

Sand

Gravel

Cobble

MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT29

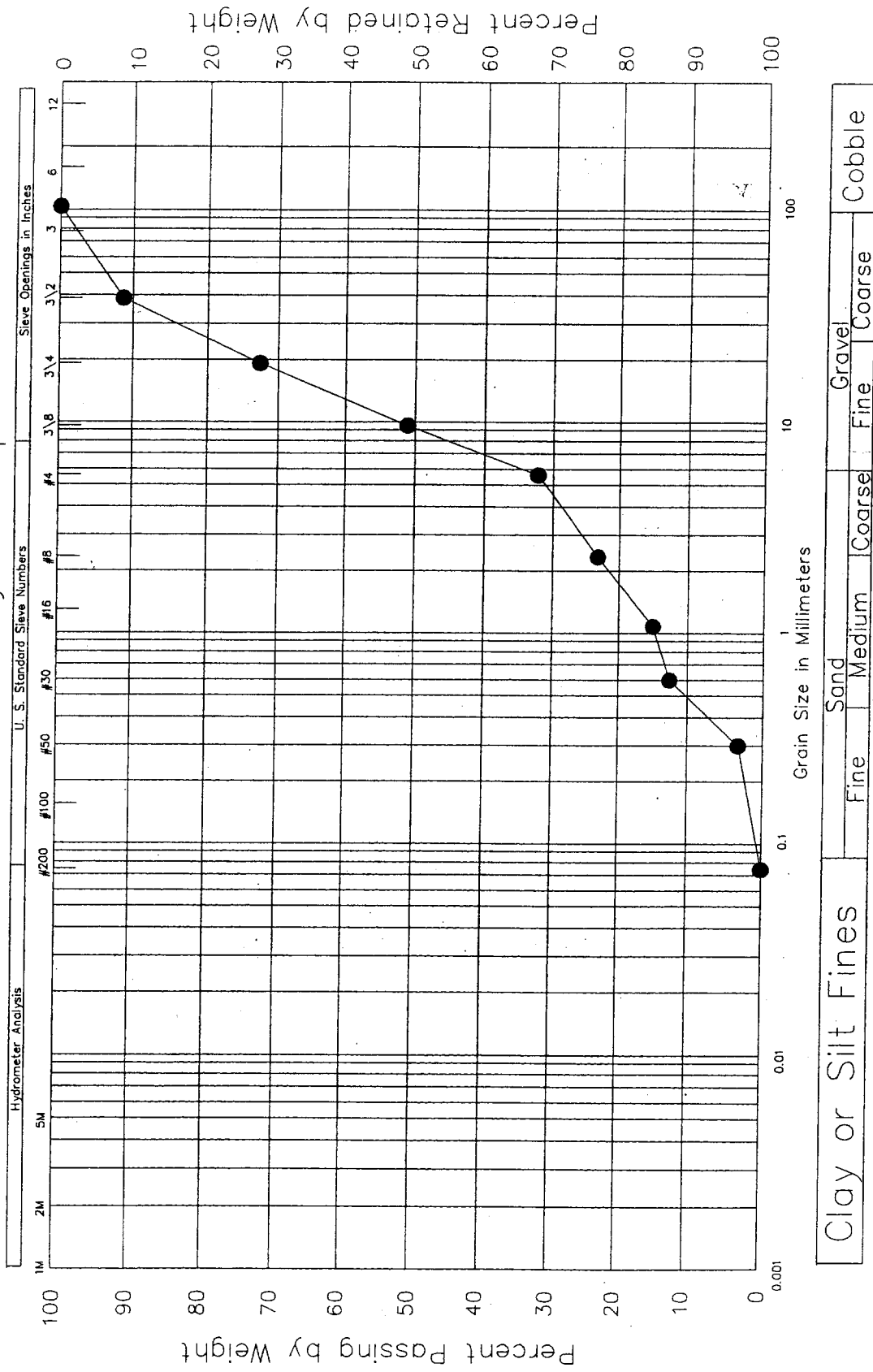
**Grain Size Distribution Data**

Grain Size (mm)	Sieve / Method	Percent Passing (%)	Percent Retained (%)
0.075	#200	~100	0
0.15	#100	~100	0
0.3	#60	~100	0
0.6	#30	~100	0
1.18	#16	~100	0
2.5	#6	~100	0
4.75	#40	~100	0
7.5	#20	~100	0
15	#10	~100	0
30	#60	~100	0
60	#30	~100	0
125	#12	~100	0
250	#6	~100	0
500	#3	~100	0
1000	#1.5	~100	0
2000	#0.75	~100	0
4000	#0.375	~100	0
8000	#0.19	~100	0
16000	#0.095	~100	0
32000	#0.0475	~100	0
64000	#0.025	~100	0
128000	#0.0125	~100	0
256000	#0.00625	~100	0
512000	#0.003125	~100	0
1024000	#0.0015625	~100	0

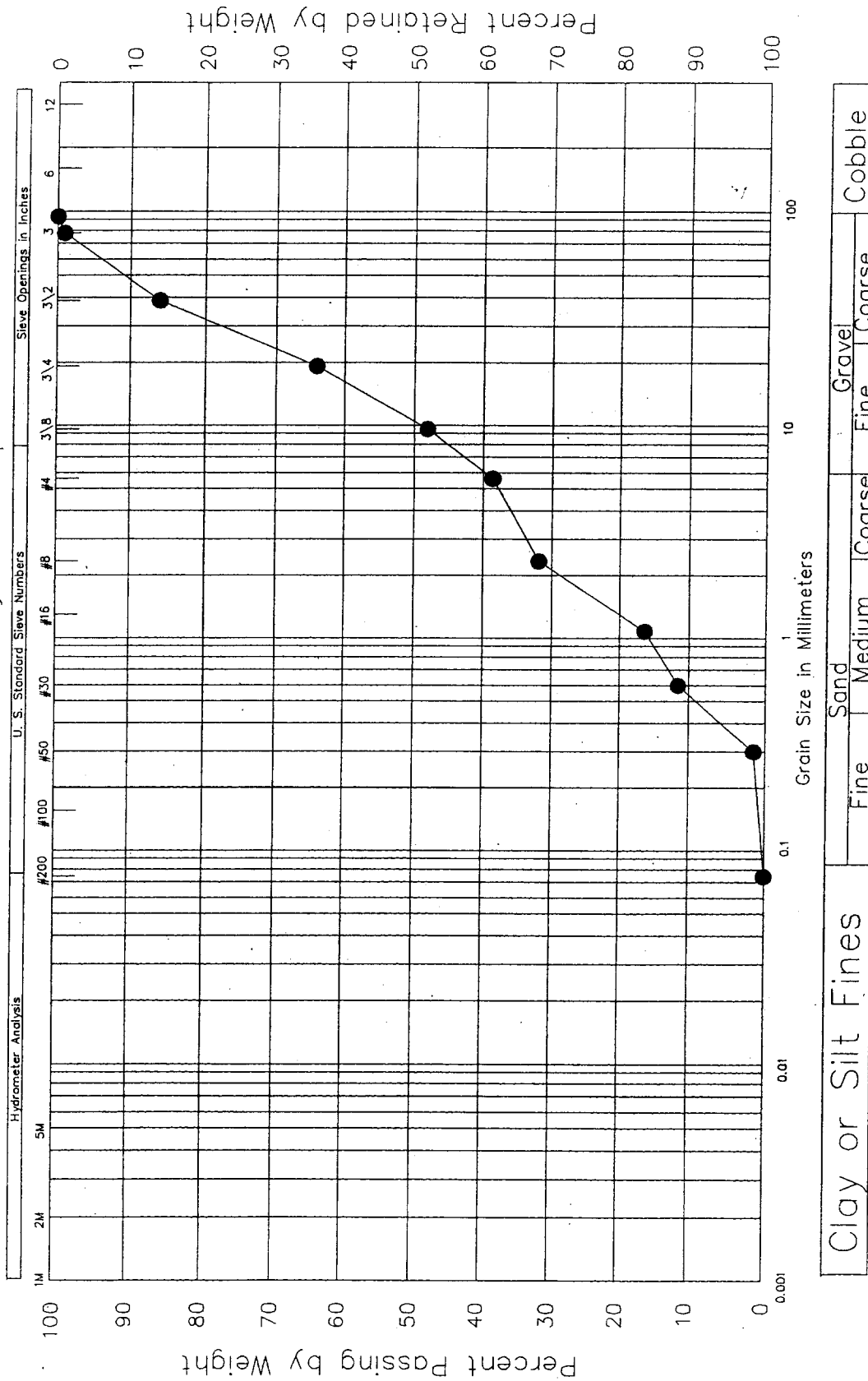
**Soil Classification:** Clay or Silt Fines

MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT30

# Mechanical Analysis Graph



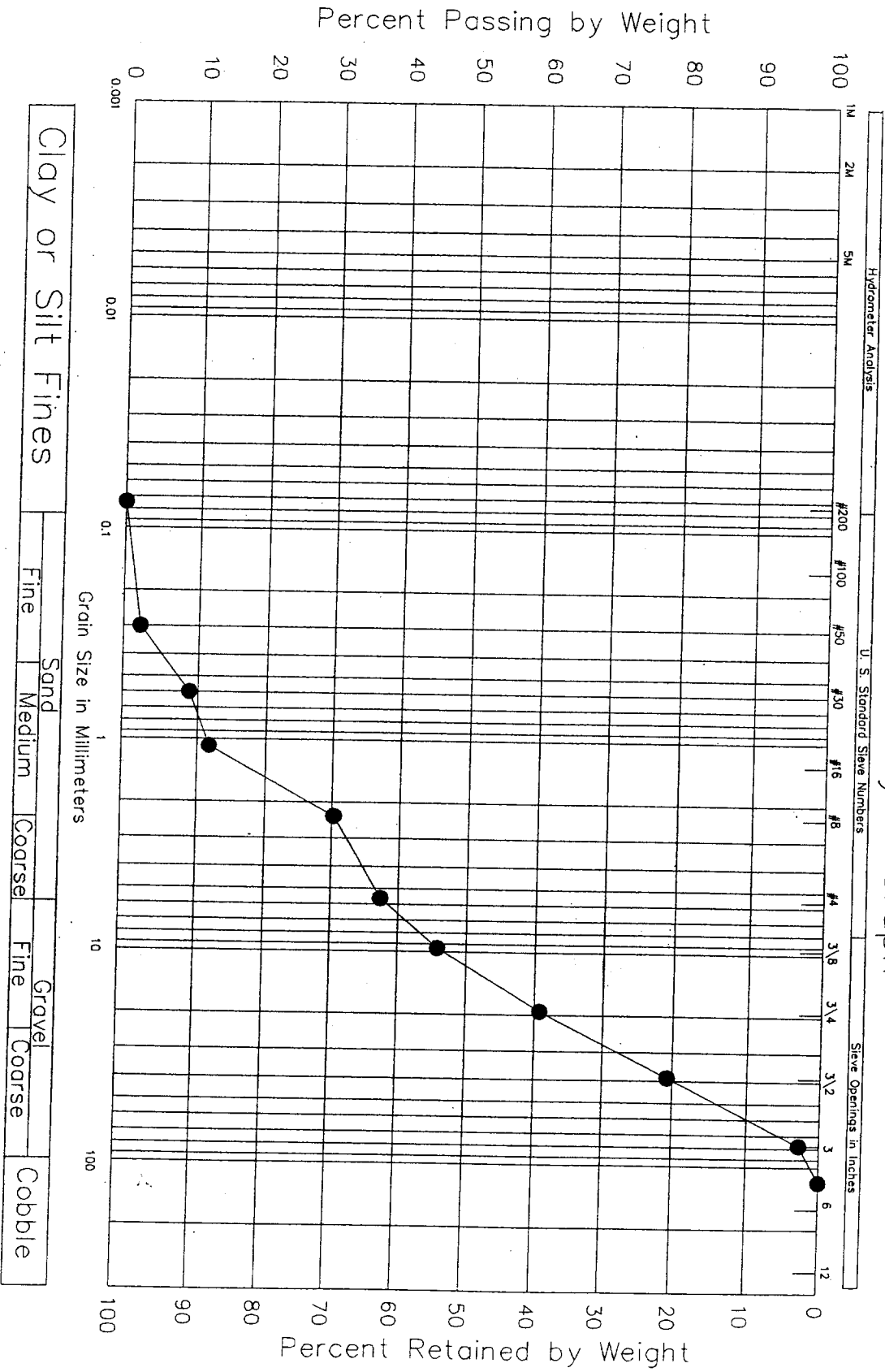
# Mechanical Analysis Graph



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT32

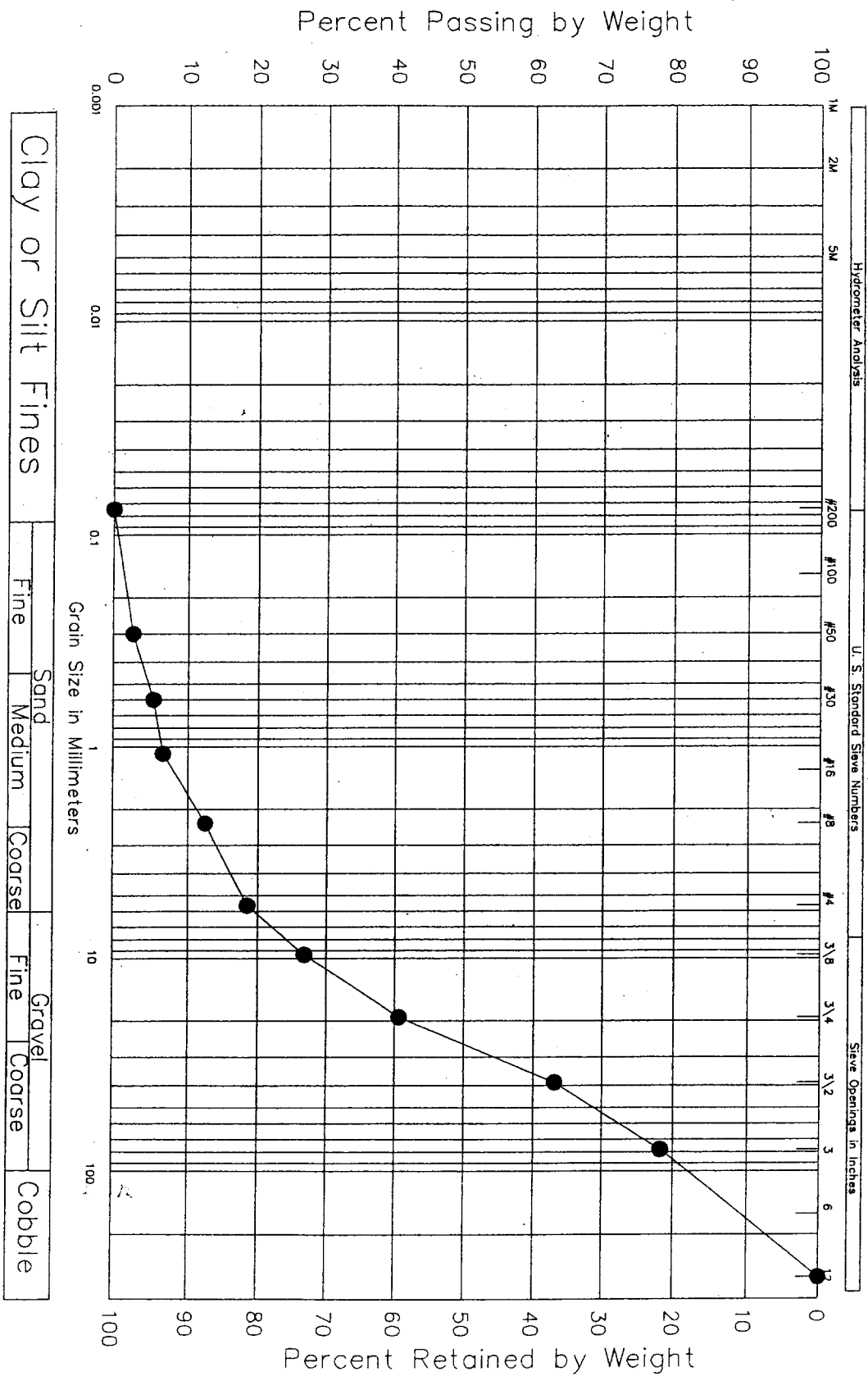


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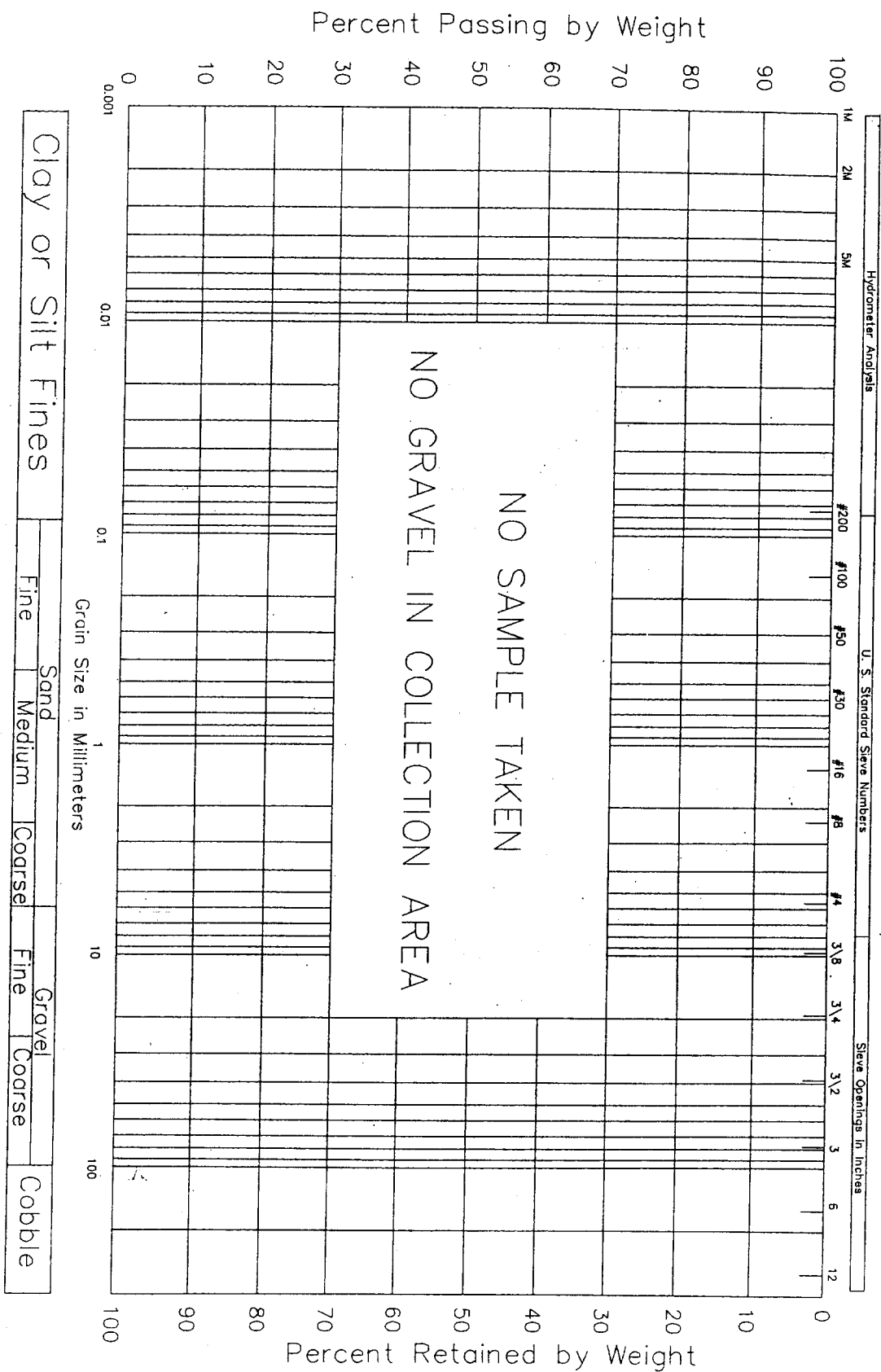
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SITE: SACT33

# Mechanical Analysis Graph



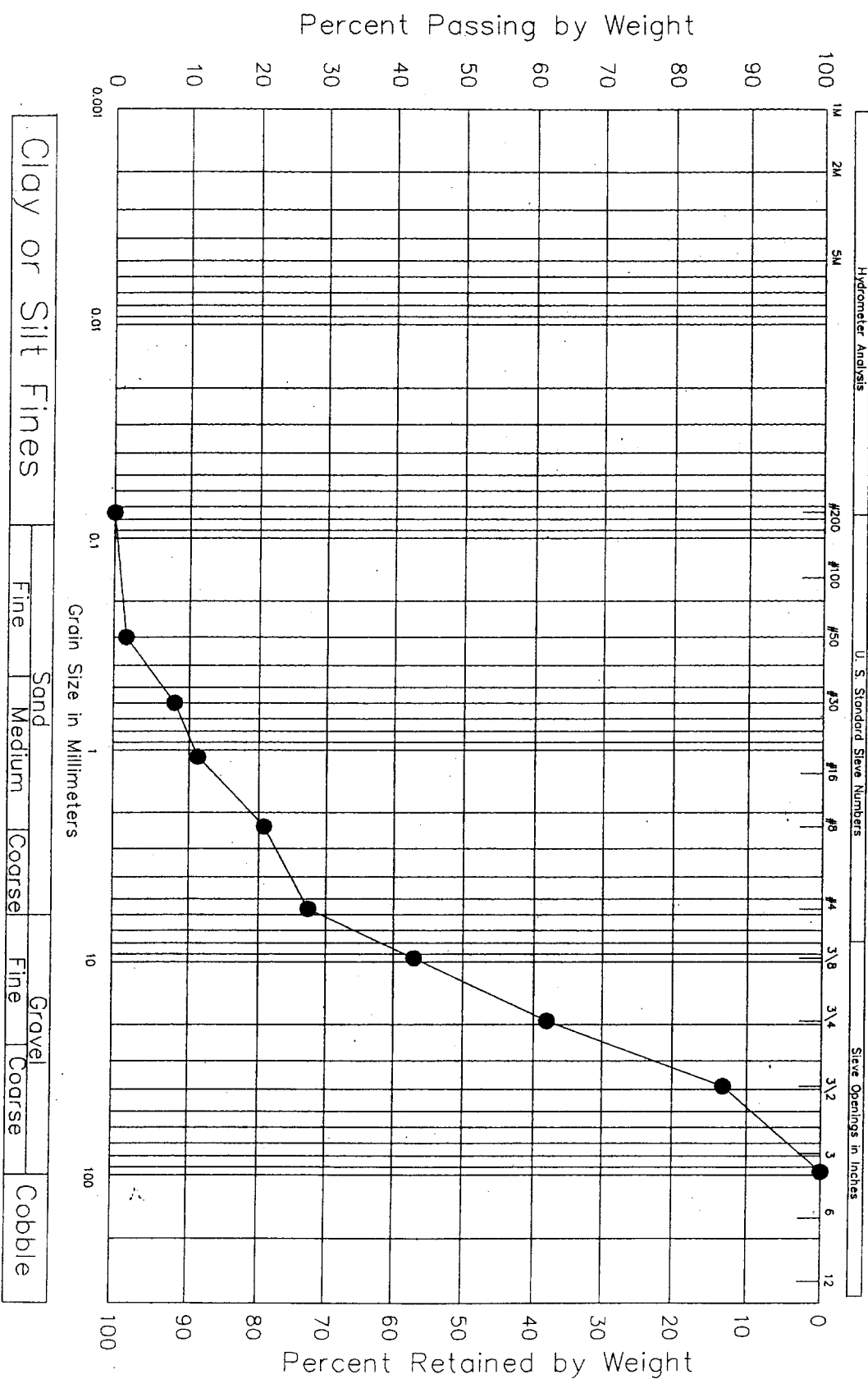
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT34

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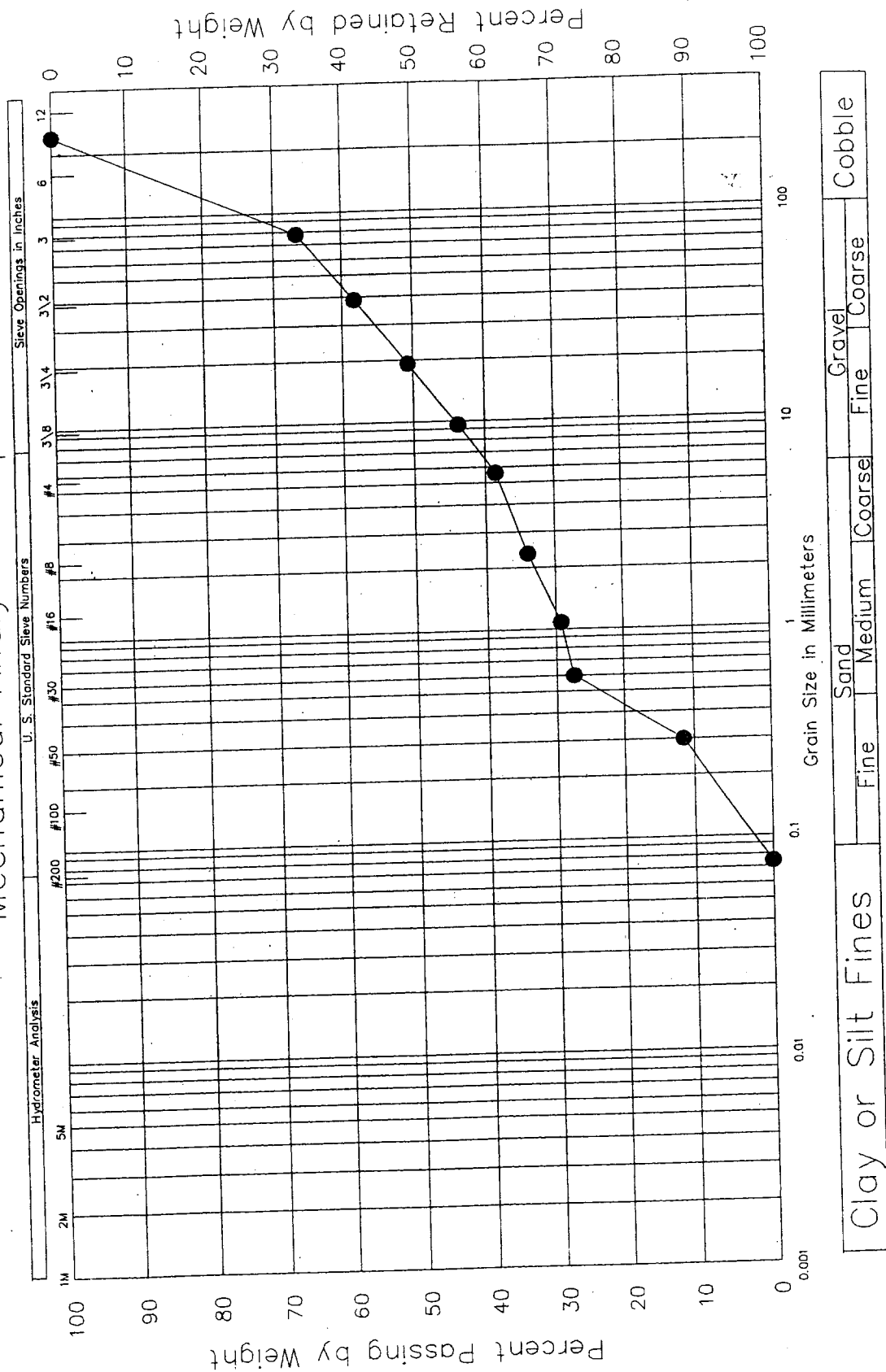
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT35

# Mechanical Analysis Graph



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT36

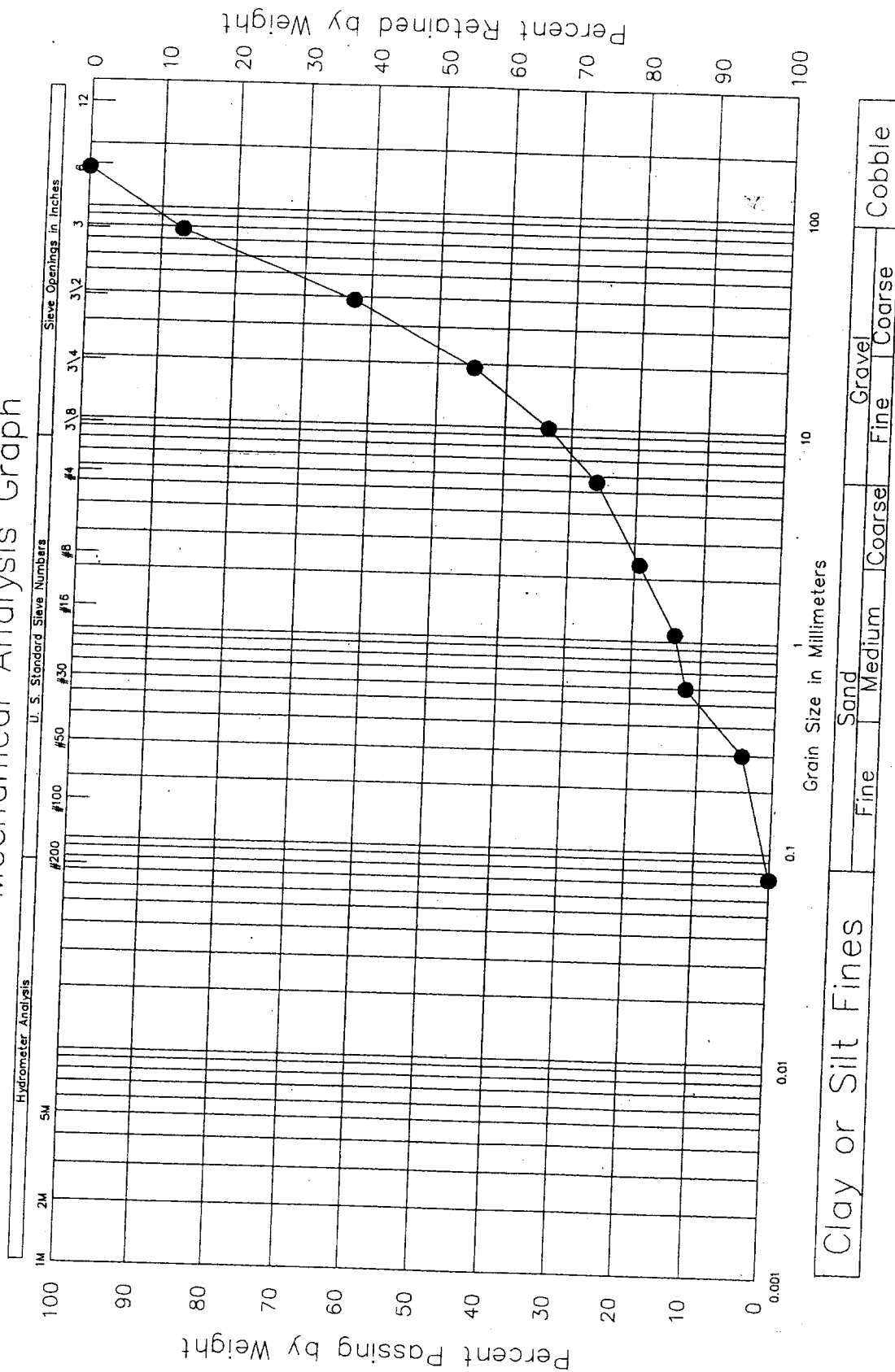
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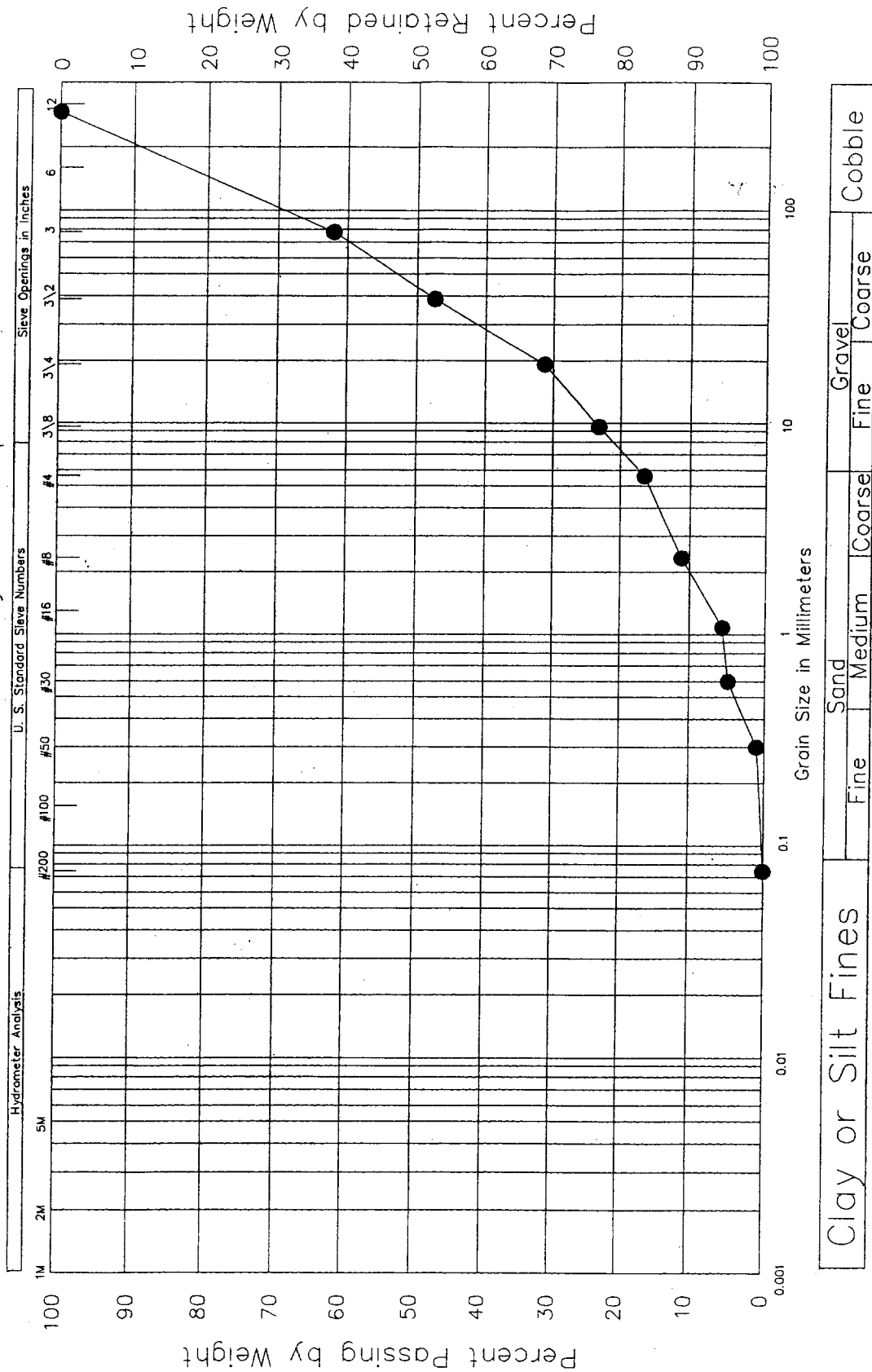
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER

SITE: SACT37

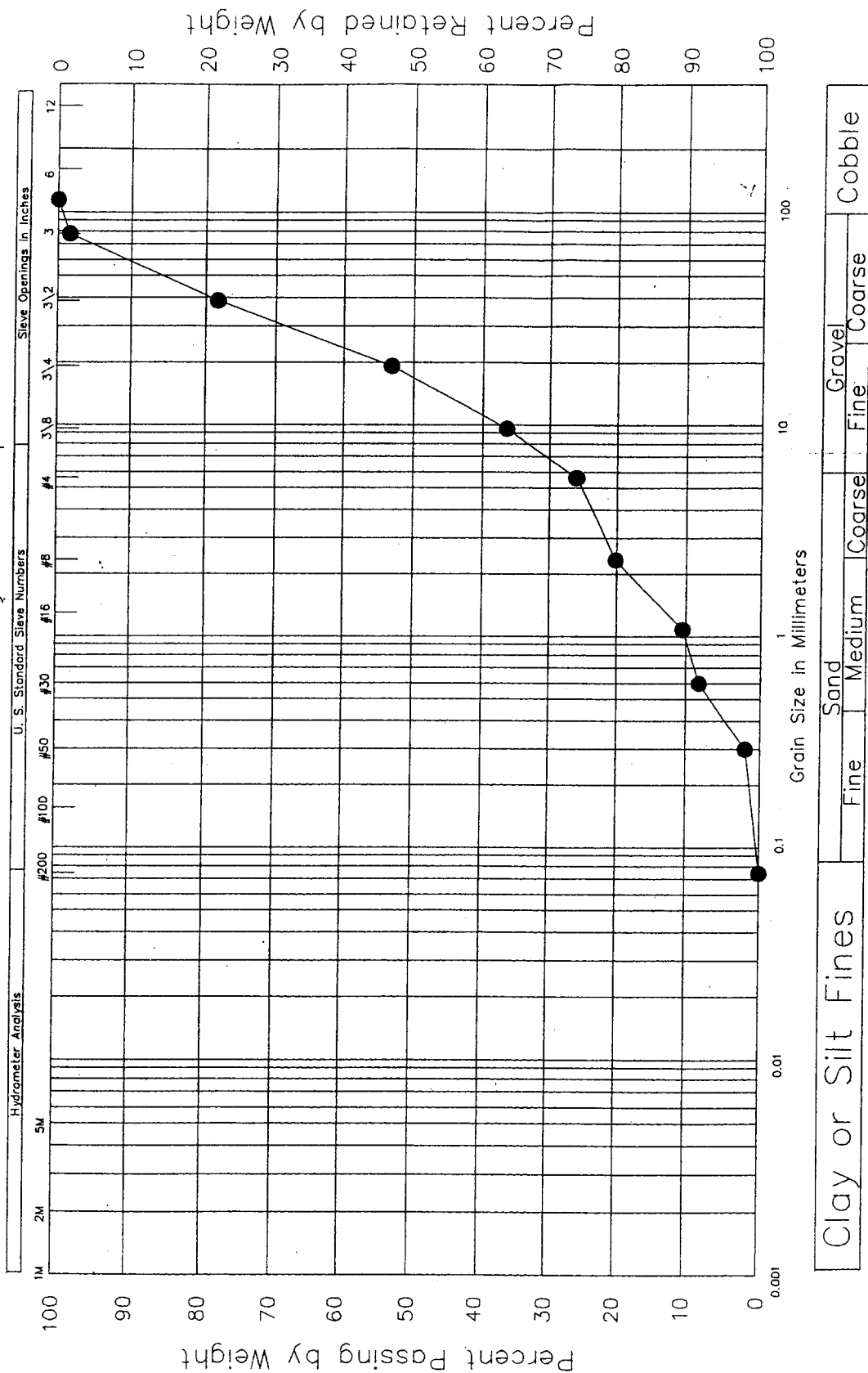
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# Mechanical Analysis Graph

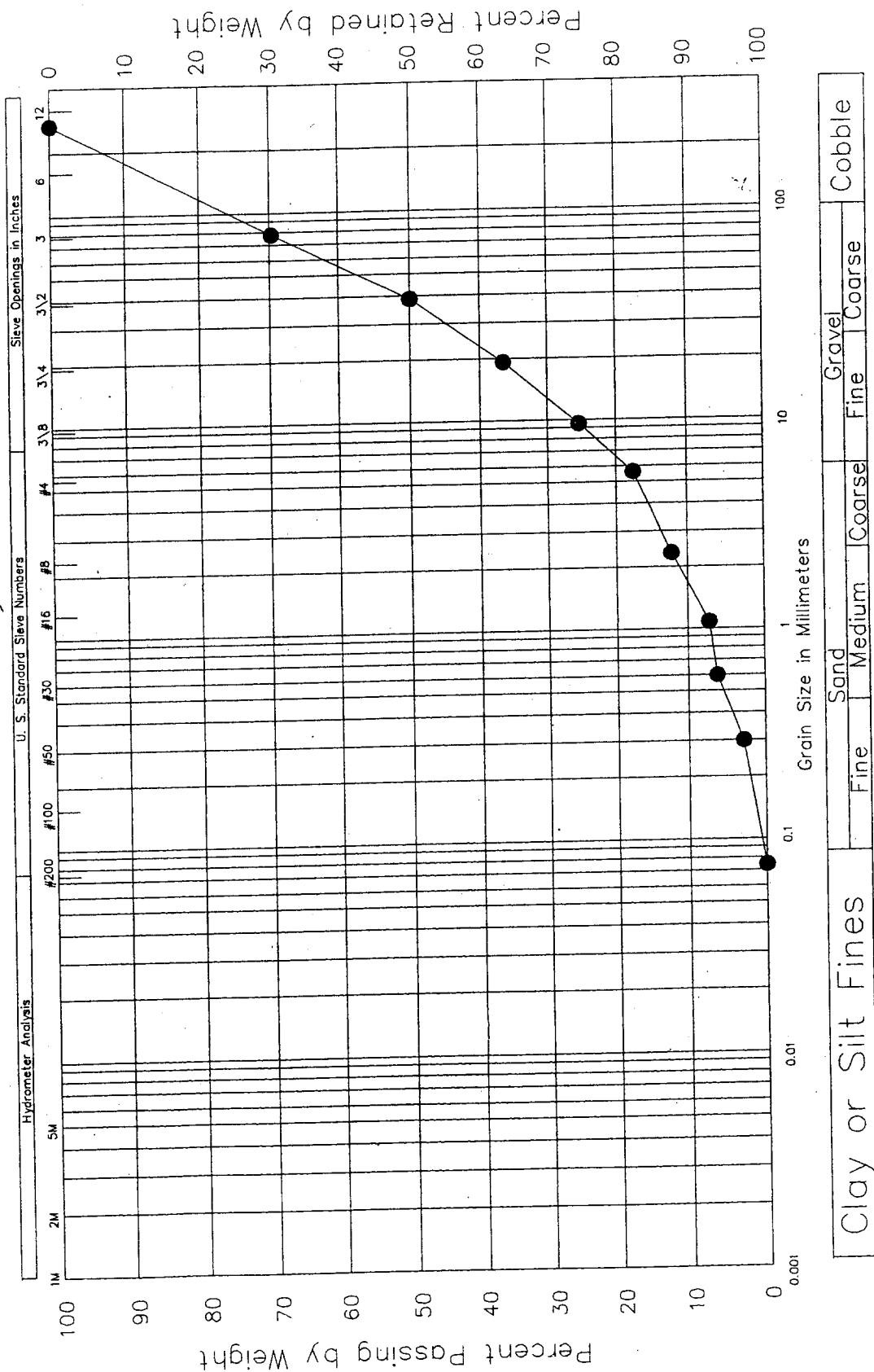


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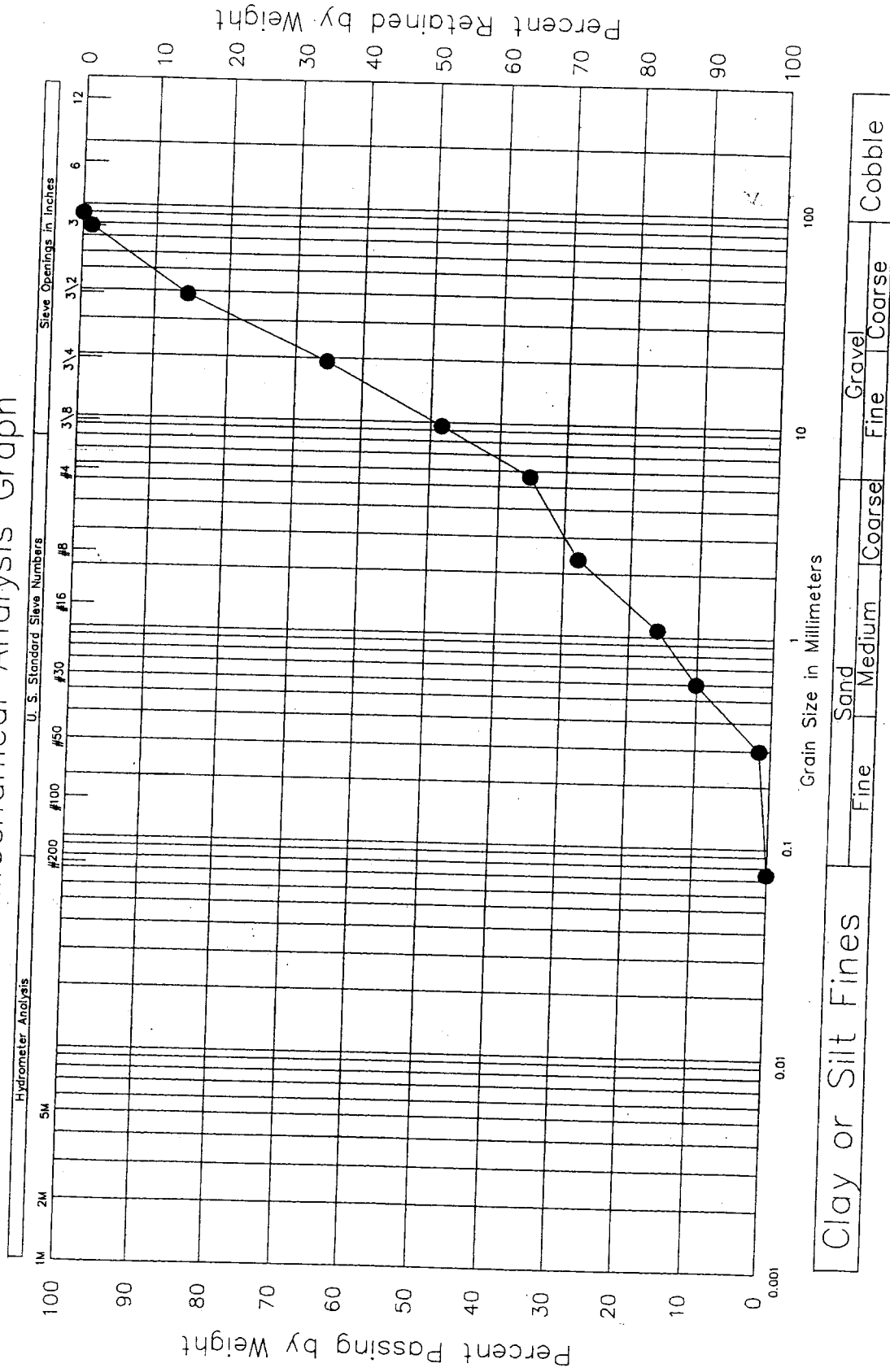
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MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER

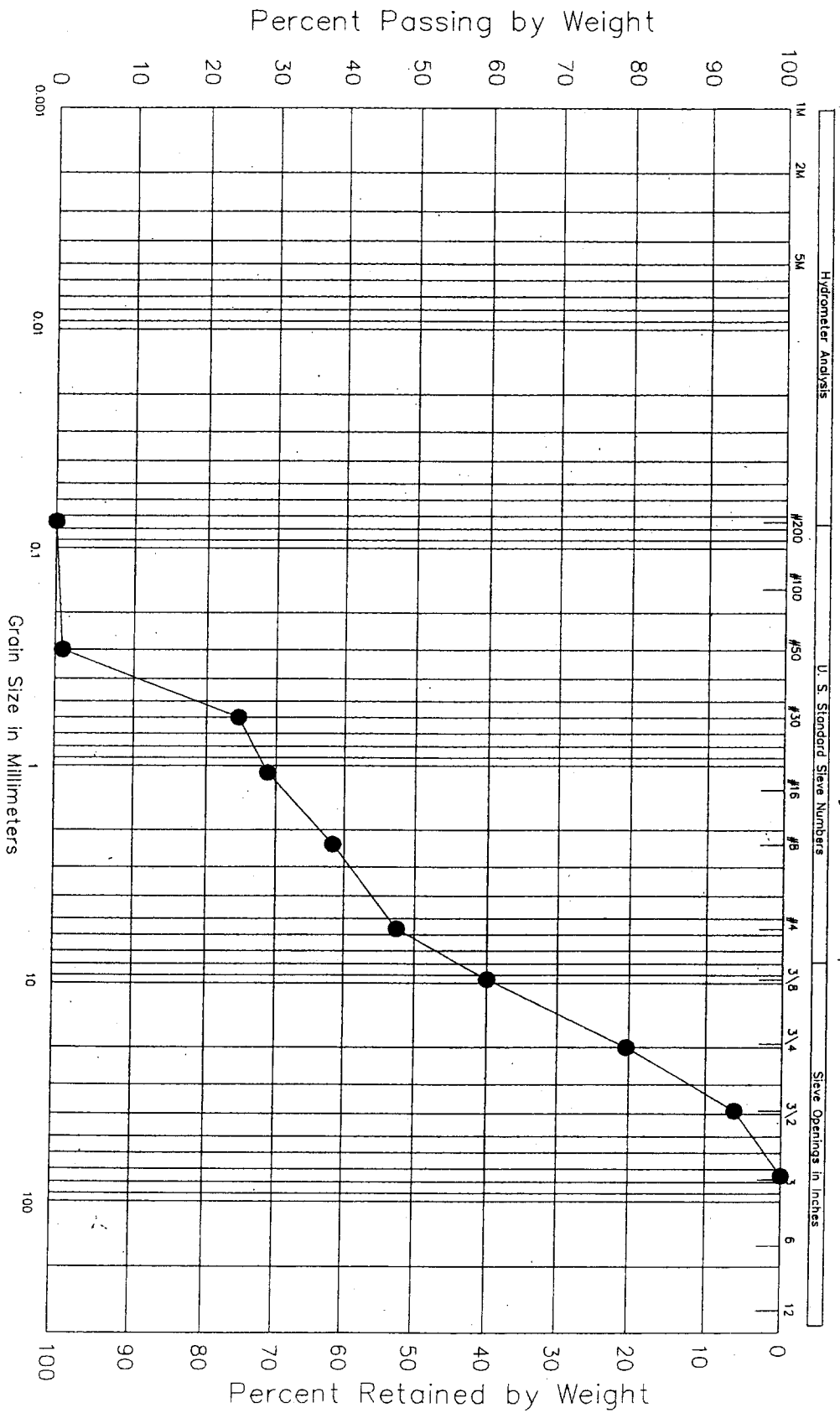
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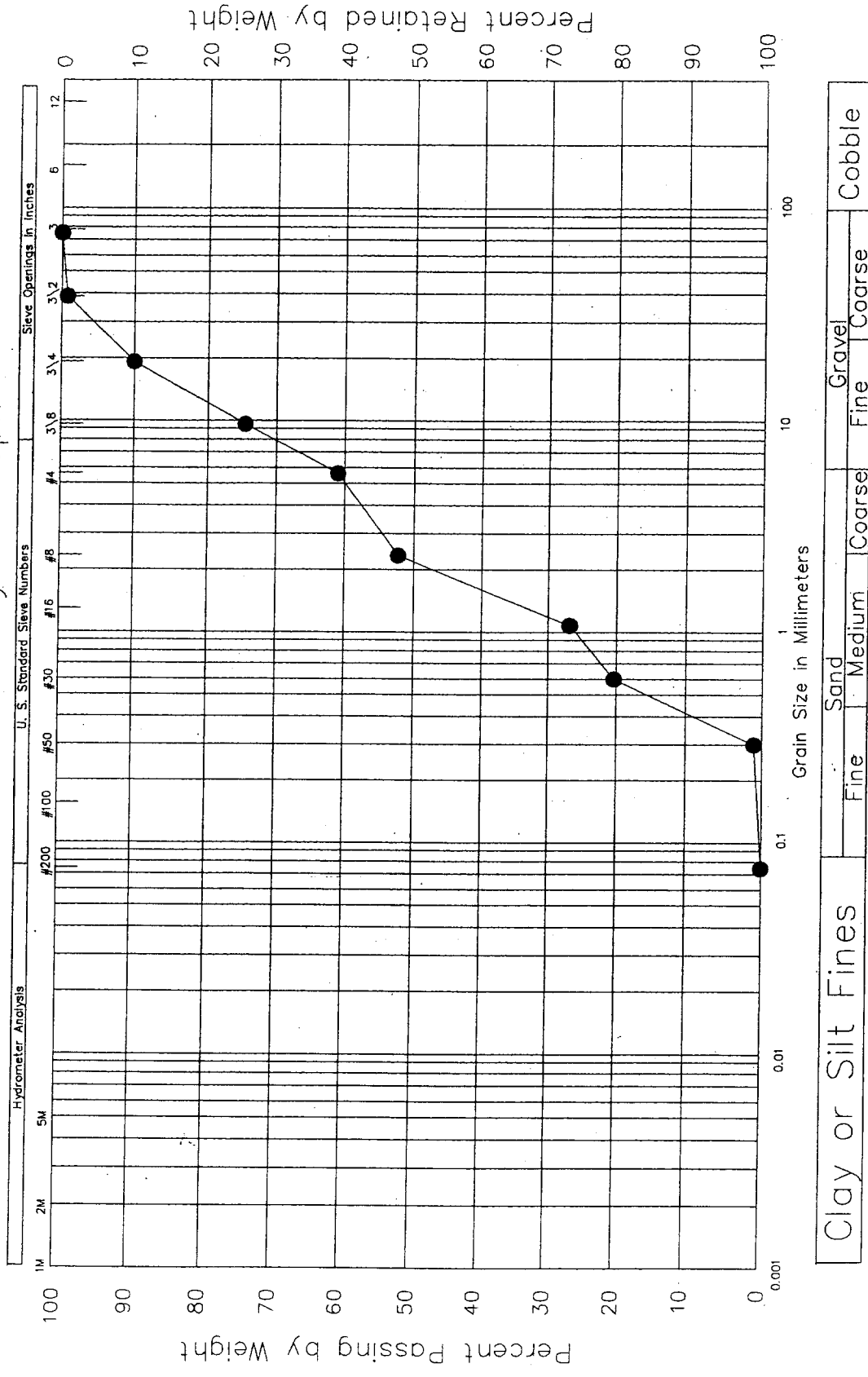
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SITE: SACT42

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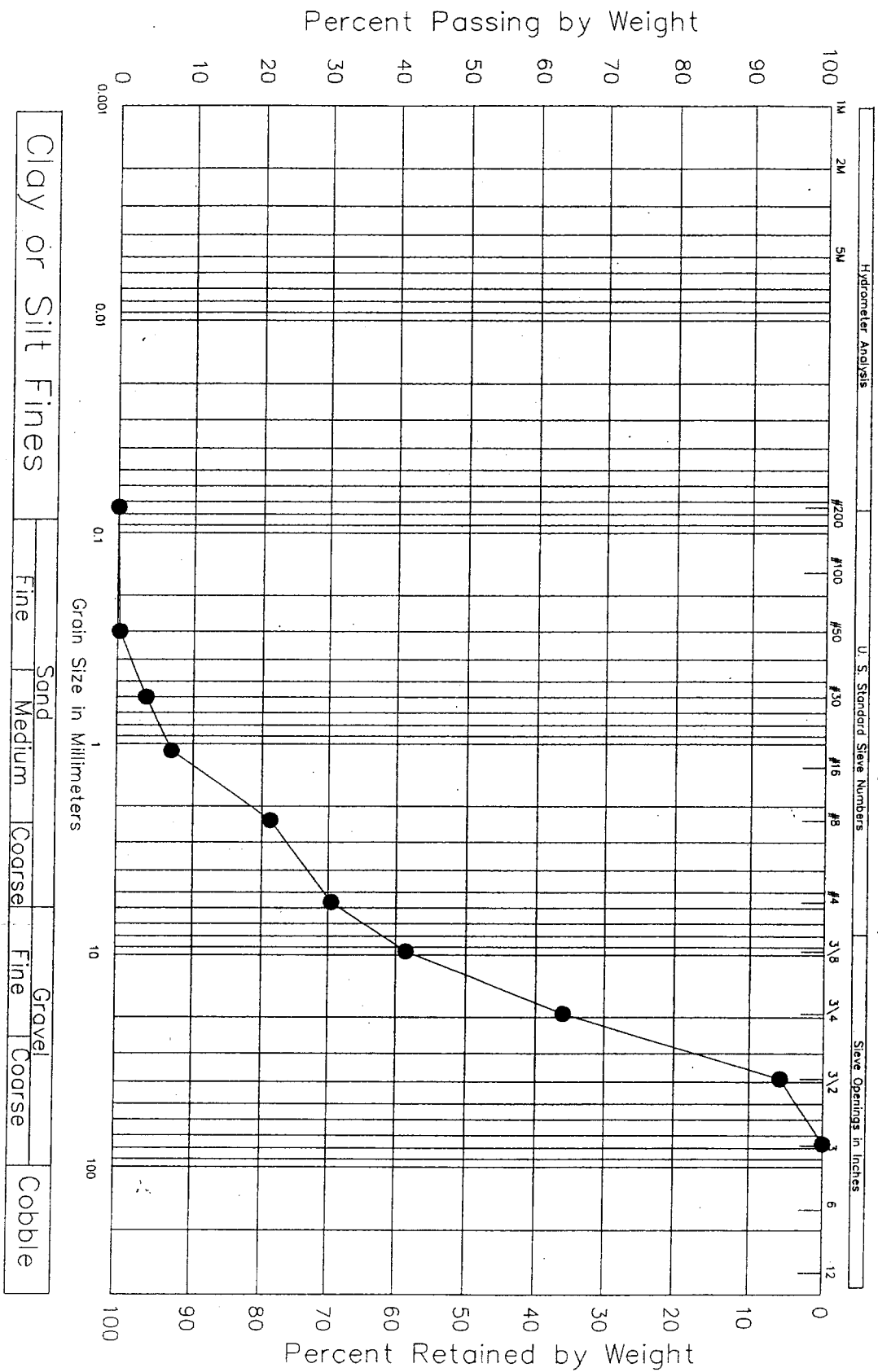


MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT43

# Mechanical Analysis Graph

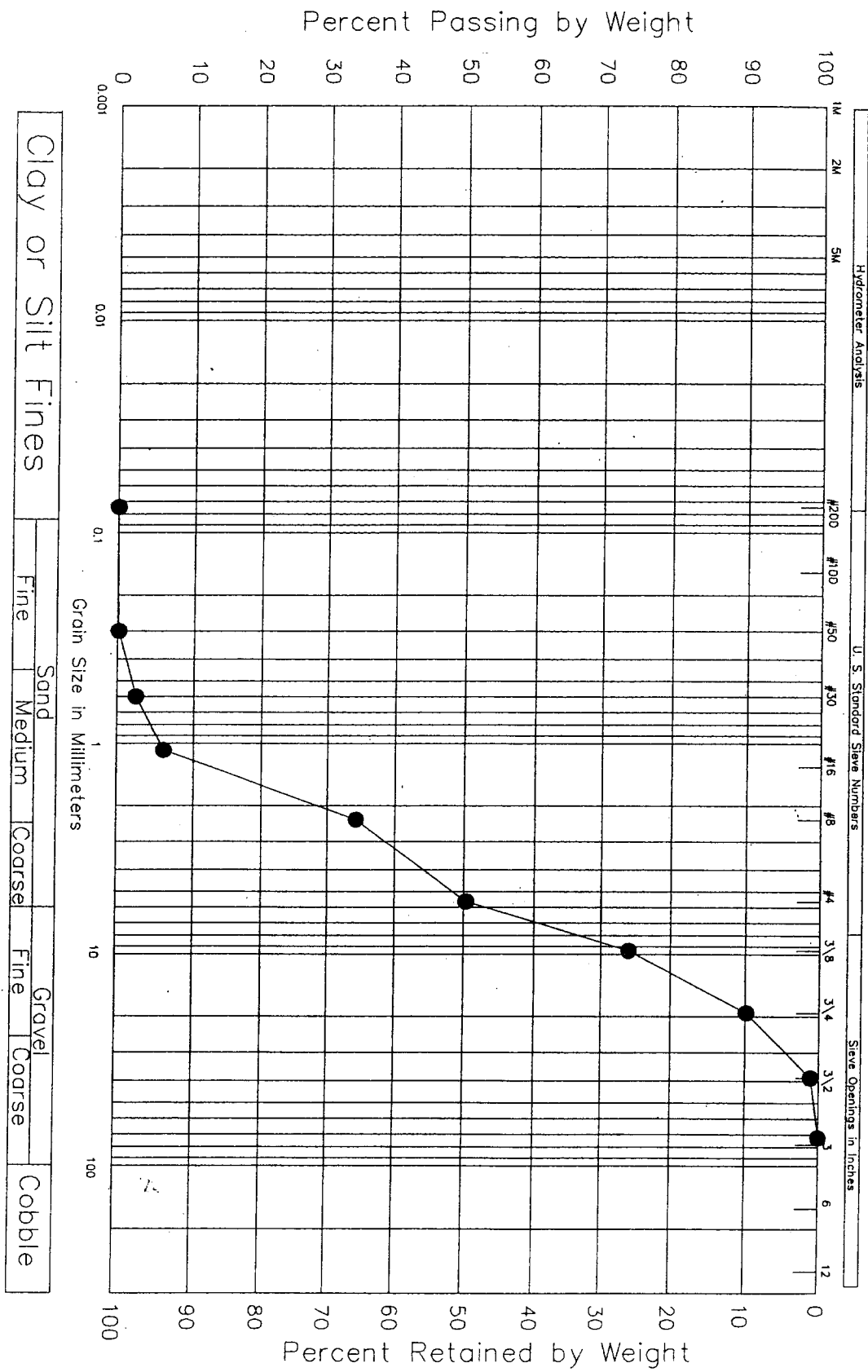


# Mechanical Analysis Graph



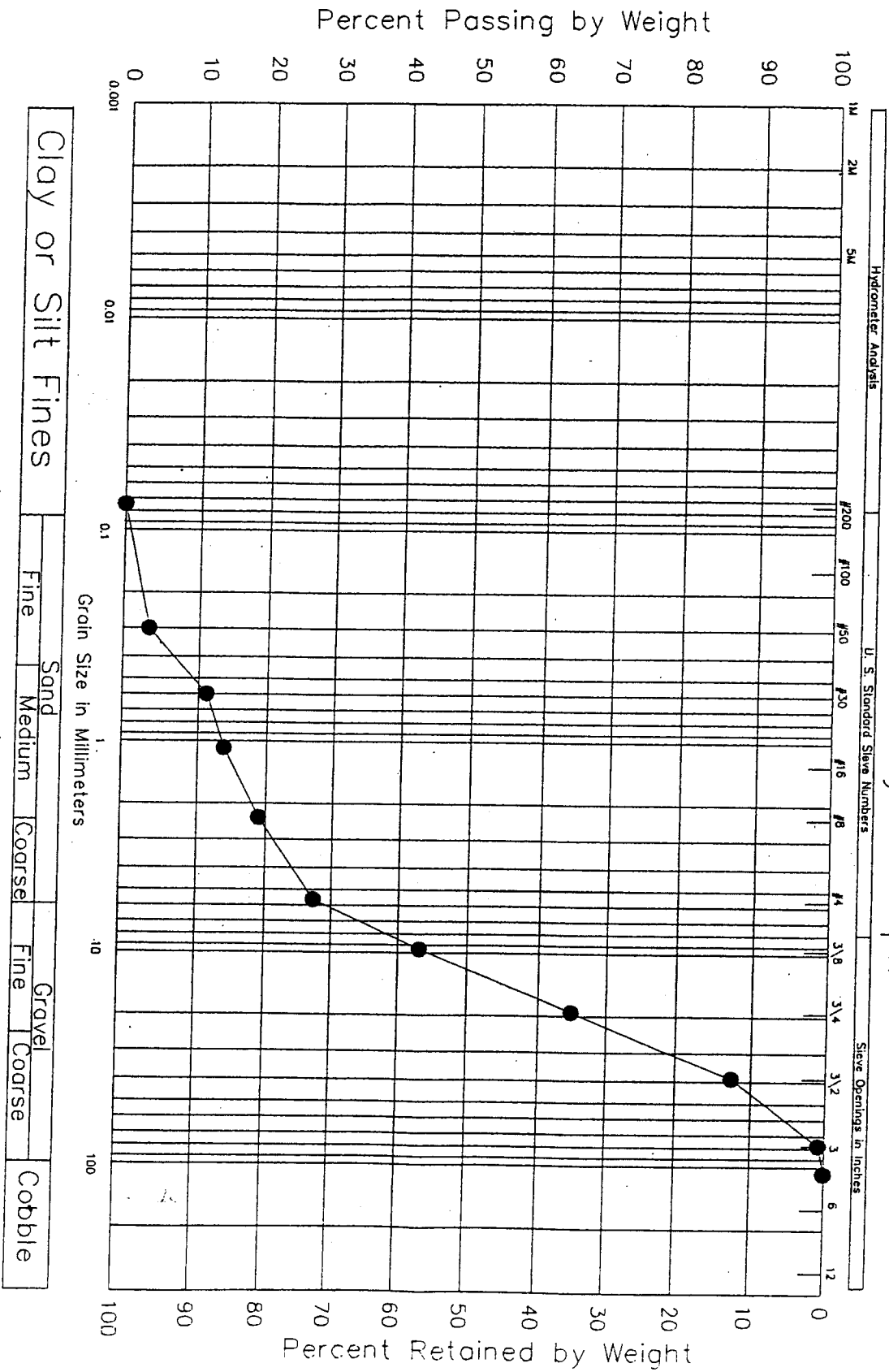
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT45

# Mechanical Analysis Graph



MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT46

# Mechanical Analysis Graph

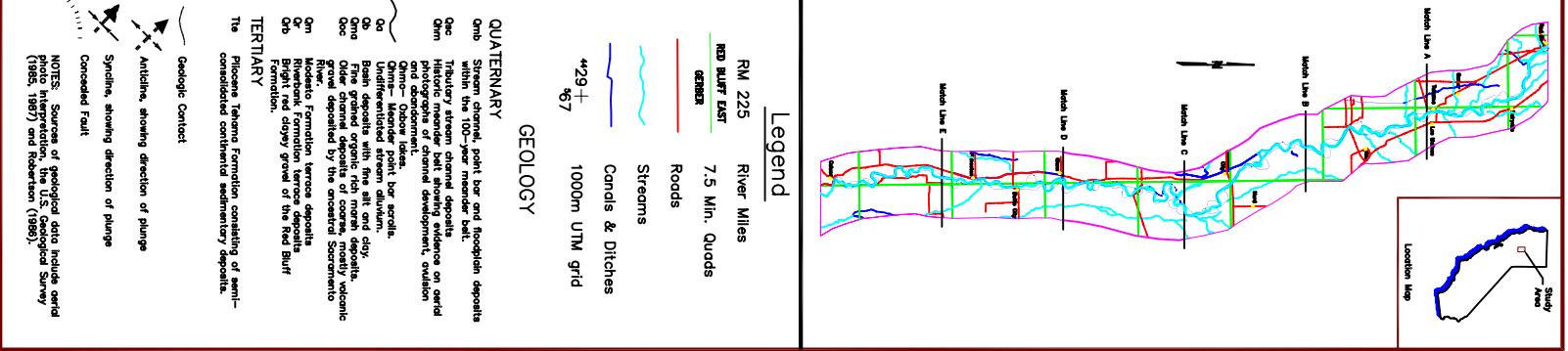


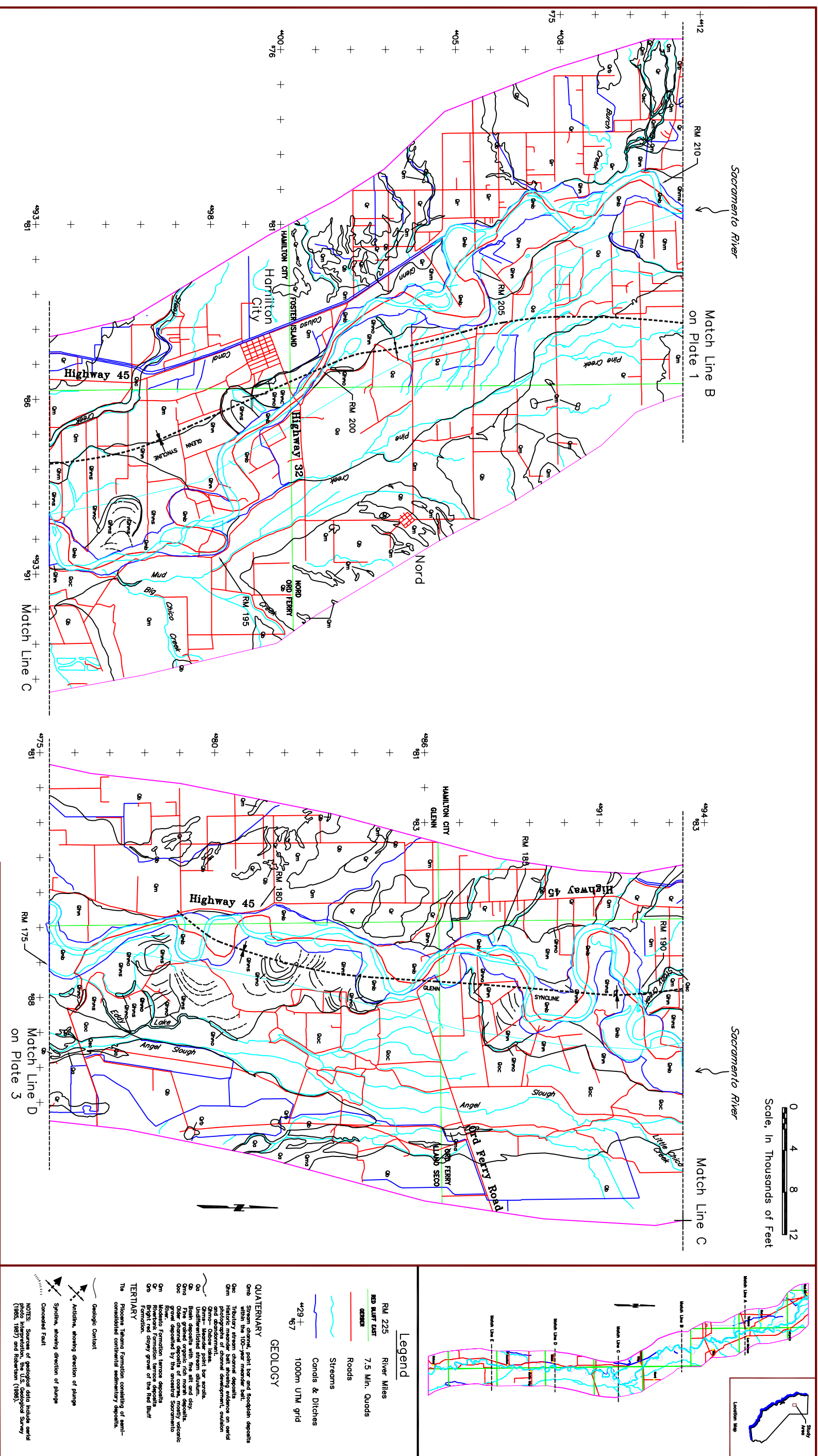
MECHANICAL ANALYSIS OF THE SACRAMENTO RIVER  
SITE: SACT47

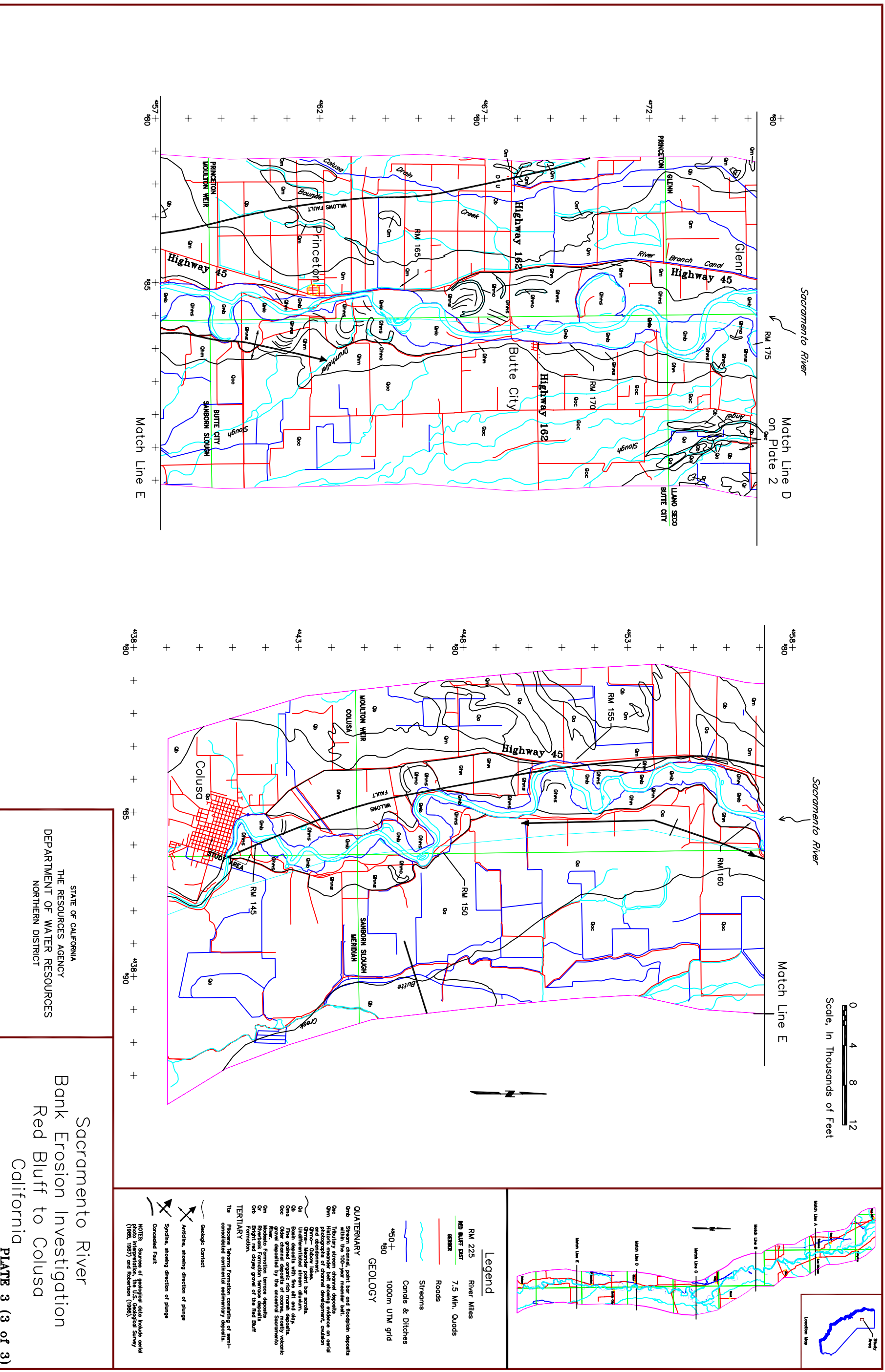
## CONVERSION FACTORS

Quantity	To Convert from Metric Unit	To Customary Unit	Multiply Metric Unit By	To Convert to Metric Unit Multiply Customary Unit By
Length	millimetres (mm)	inches (in)	0.03937	25.4
	centimetres (cm) for snow depth	inches (in)	0.3937	2.54
	metres (m)	feet (ft)	3.2808	0.3048
	kilometres (km)	miles (mi)	0.62139	1.6093
Area	square millimetres (mm <sup>2</sup> )	square inches (in <sup>2</sup> )	0.00155	645.16
	square metres (m <sup>2</sup> )	square feet (ft <sup>2</sup> )	10.764	0.092903
	hectares (ha)	acres (ac)	2.4710	0.40469
	square kilometres (km <sup>2</sup> )	square miles (mi <sup>2</sup> )	0.3861	2.590
Volume	litres (L)	gallons (gal)	0.26417	3.7854
	megalitres	million gallons (10 <sup>6</sup> gal)	0.26417	3.7854
	cubic metres (m <sup>3</sup> )	cubic feet (ft <sup>3</sup> )	35.315	0.028317
	cubic metres (m <sup>3</sup> )	cubic yards (yd <sup>3</sup> )	1.308	0.76455
	cubic dekametres (dam <sup>3</sup> )	acre-feet (ac-ft)	0.8107	1.2335
Flow	cubic metres per second (m <sup>3</sup> /s)	cubic feet per second (ft <sup>3</sup> /s)	35.315	0.028317
	litres per minute (L/min)	gallons per minute (gal/min)	0.26417	3.7854
	litres per day (L/day)	gallons per day (gal/day)	0.26417	3.7854
	megalitres per day (ML/day)	million gallons per day (mgd)	0.26417	3.7854
	cubic dekametres per day (dam <sup>3</sup> /day)	acre-feet per day (ac-ft/day)	0.8107	1.2335
Mass	kilograms (kg)	pounds (lb)	2.2046	0.45359
	megagrams (Mg)	tons (short, 2,000 lb)	1.1023	0.90718
Velocity	metres per second (m/s)	feet per second (ft/s)	3.2808	0.3048
Power	kilowatts (kW)	horsepower (hp)	1.3405	0.746
Pressure	kilopascals (kPa)	pounds per square inch (psi)	0.14505	6.8948
	kilopascals (kPa)	feet head of water	0.33456	2.989
Specific Capacity	litres per minute per metre drawdown	gallons per minute per foot drawdown	0.08052	12.419
Concentration	milligrams per litre (mg/L)	parts per million (ppm)	1.0	1.0
Electrical Conductivity	microsiemens per centimetre (uS/cm)	micromhos per centimetre	1.0	1.0
Temperature	degrees Celsius (°C)	degrees Fahrenheit (°F)	$(1.8 \times ^\circ\text{C}) + 32$ $(^\circ\text{F} - 32) / 1.8$	

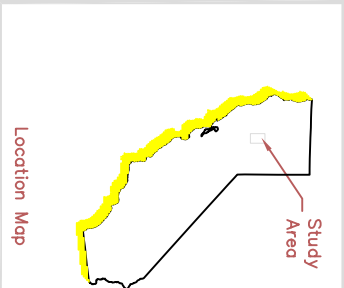
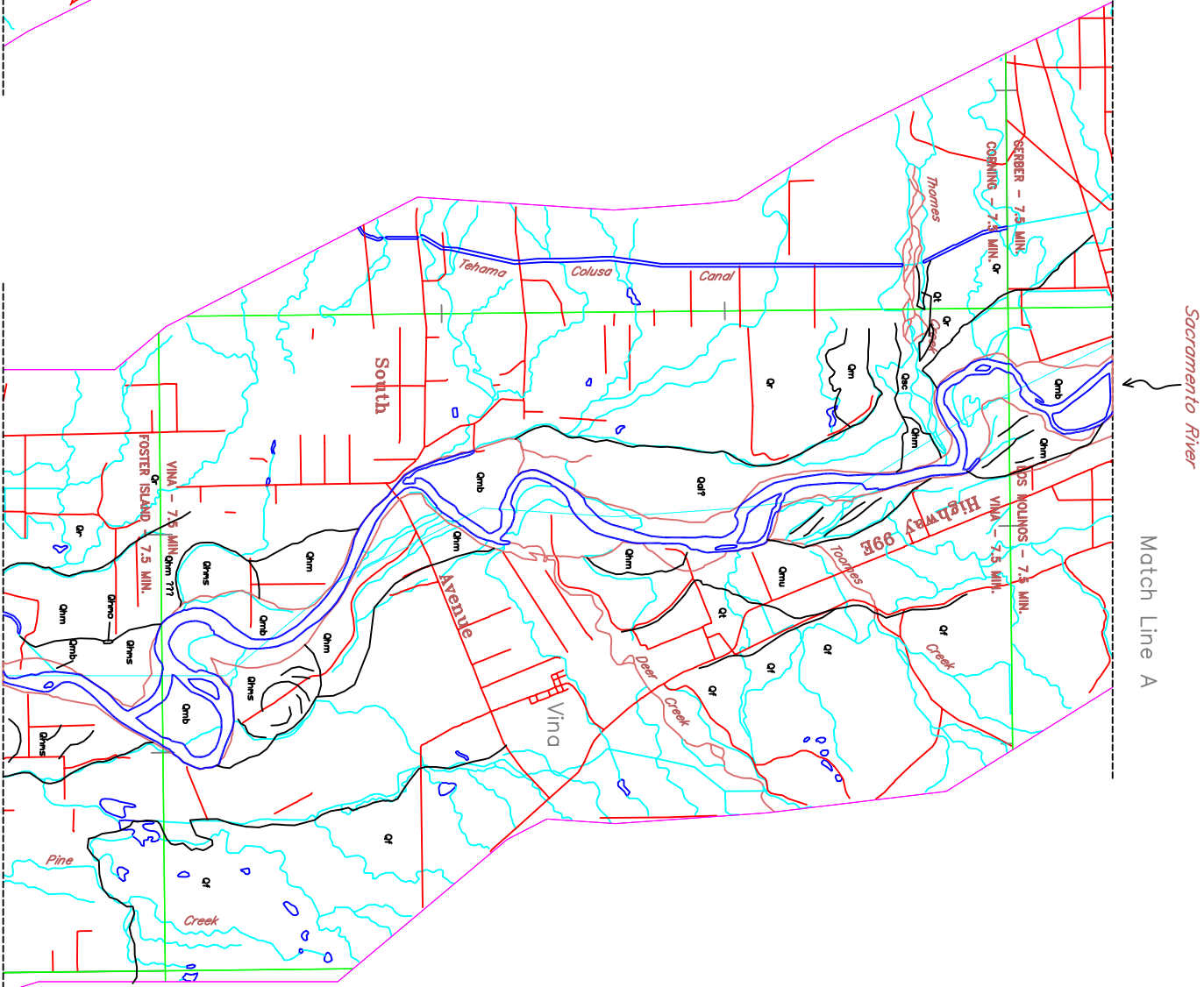
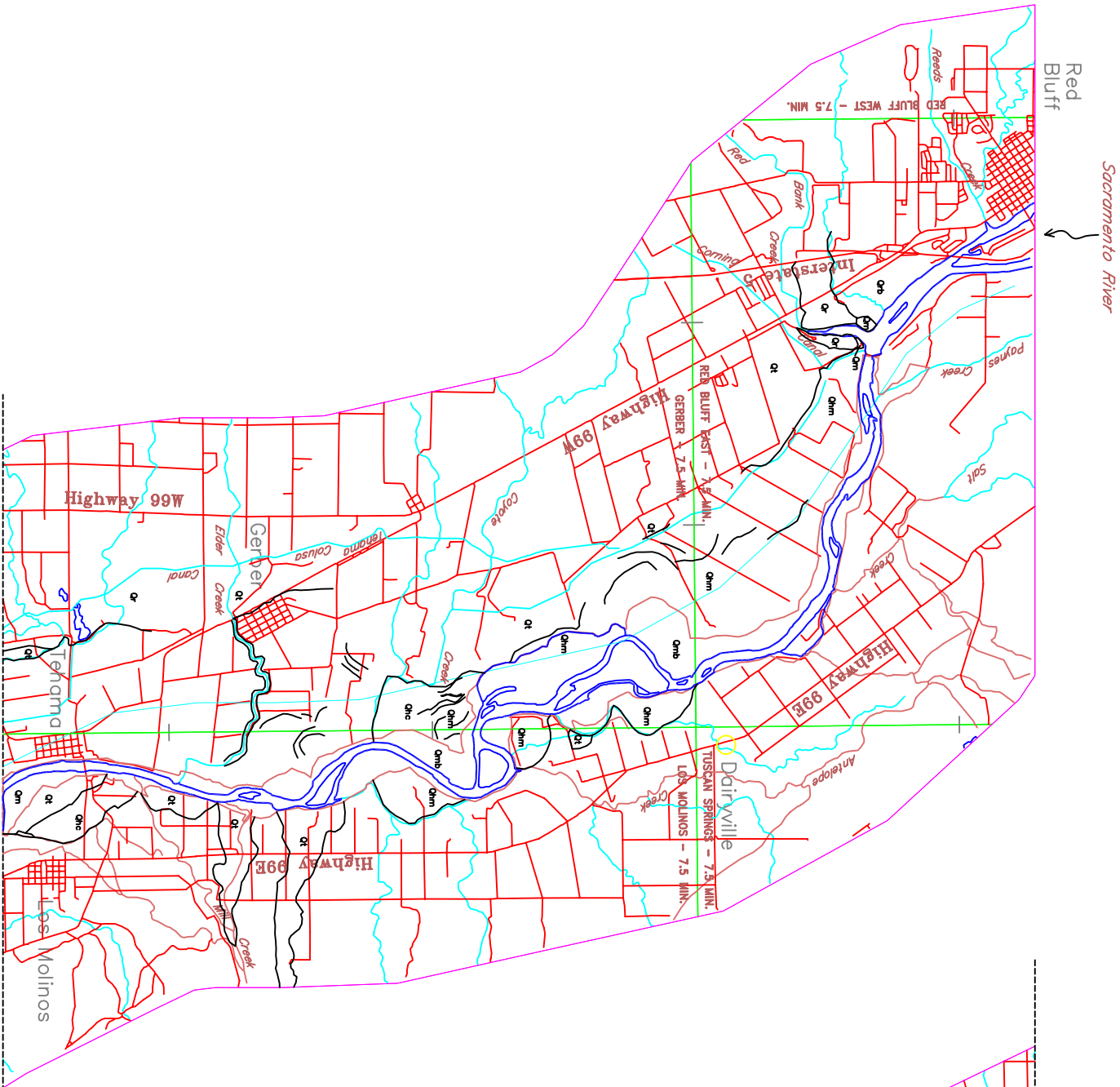






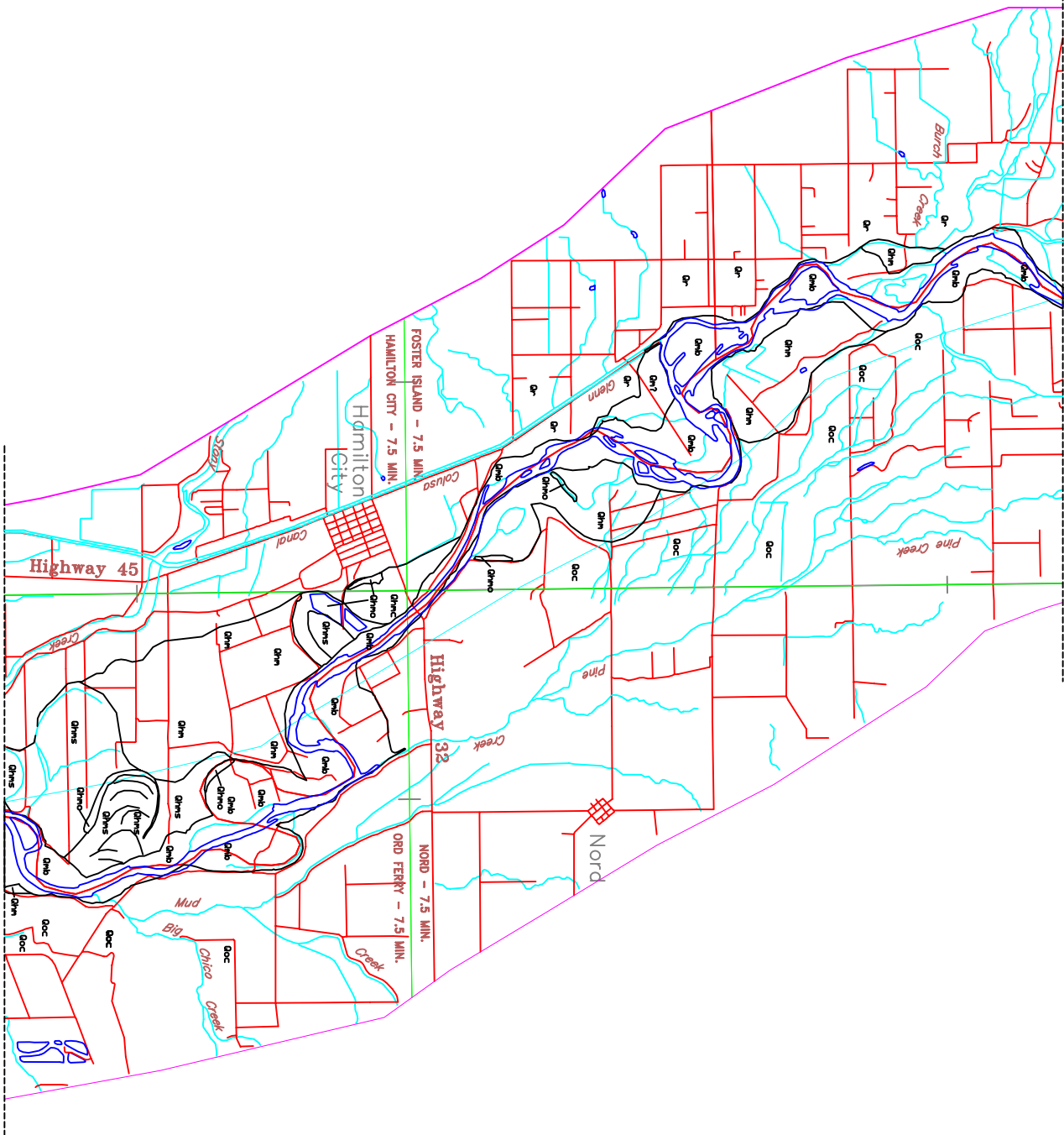






Sacramento River

Match Line B



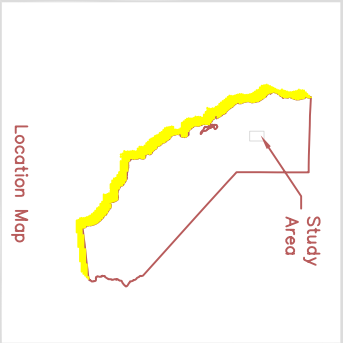
Match Line C

Sacramento River

Match Line C



Match Line D



Location Map

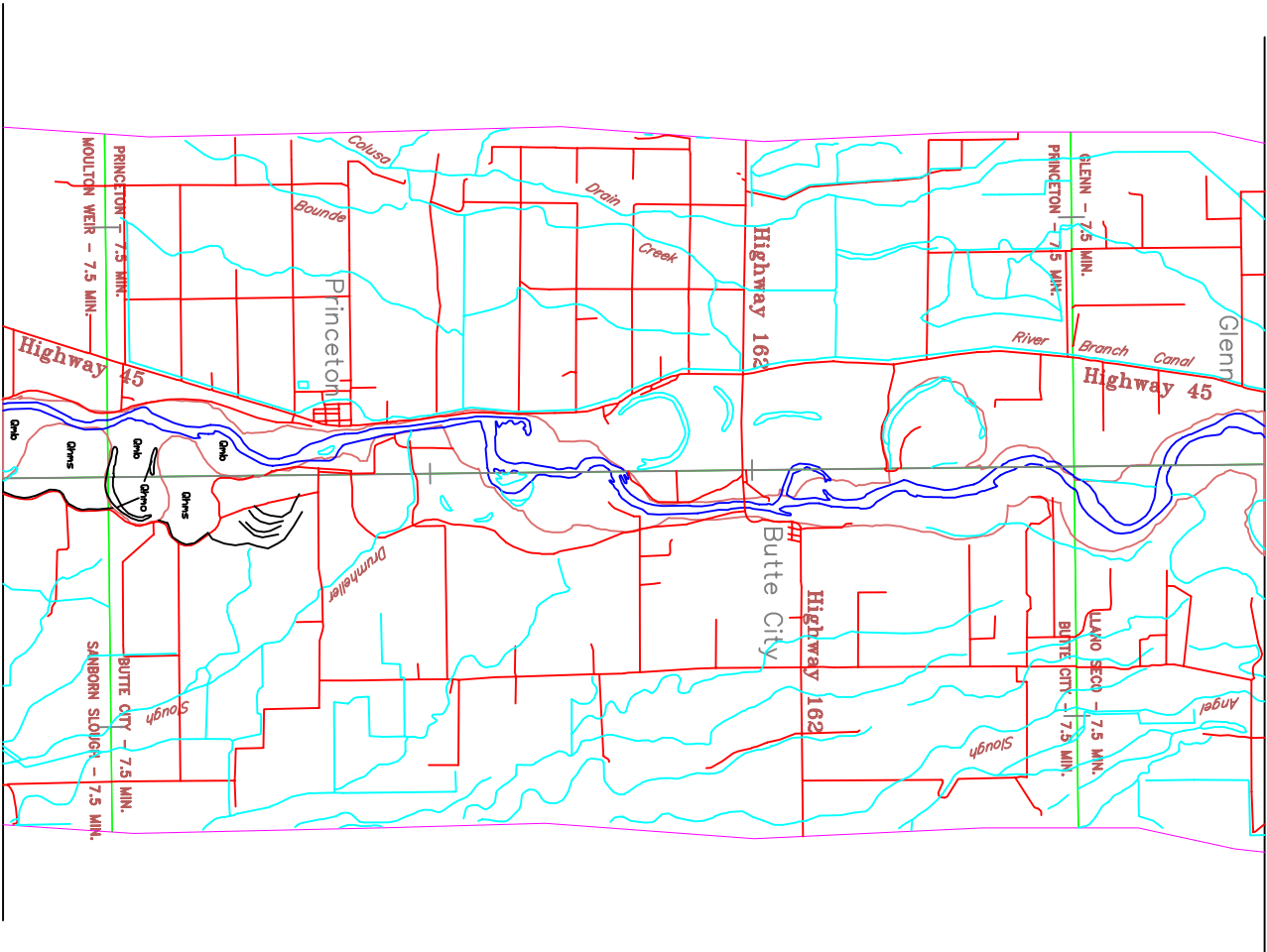


Sacramento River  
Bank Erosion Investigation  
Red Bluff to Colusa  
California

STATE OF CALIFORNIA  
THE RESOURCES AGENCY  
DEPARTMENT OF WATER RESOURCES  
NORTHERN DISTRICT

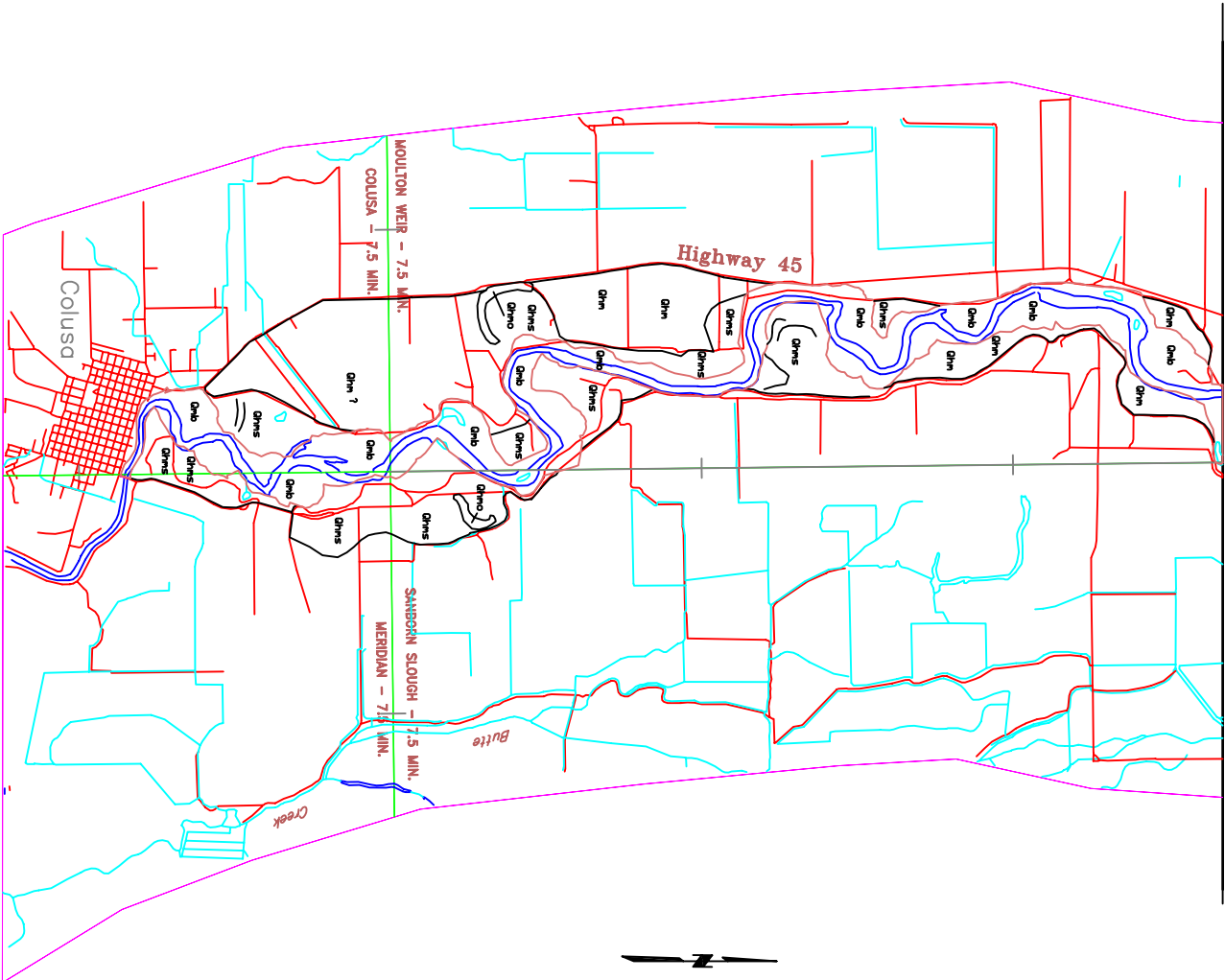
Sacramento River

Match Line D



Sacramento River

Match Line E



STATE OF CALIFORNIA  
THE RESOURCES AGENCY  
DEPARTMENT OF WATER RESOURCES  
NORTHERN DISTRICT

Sacramento River  
Bank Erosion Investigation  
Red Bluff to Colusa  
California









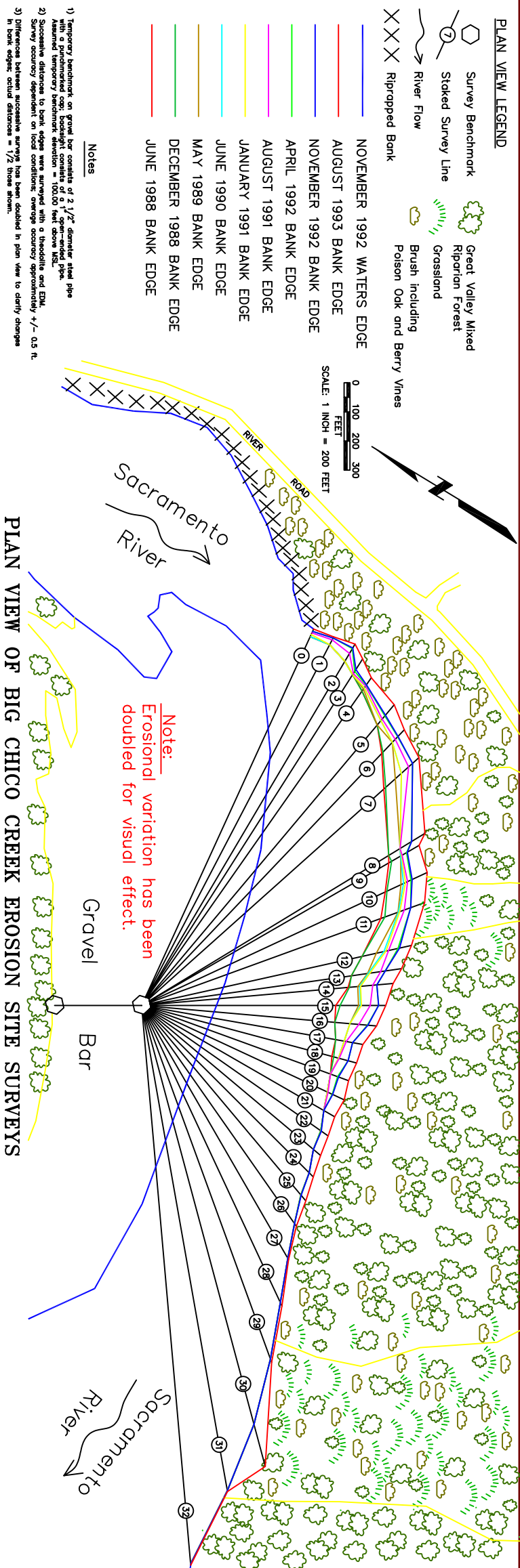












**BANK FEATURES PROFILE**

ALL VALUES ARE PERCENTAGES WITH CIRCLES REPRESENTING 100 %

A: BARE  
B: GRASS  
C: STAR THISTLES

E: VINES  
F: SHRUBS  
G: TREES

J: BANK SWALLOWS  
K: WILLOWS  
M: ROOTS

**UNIFIED SOIL CLASSIFICATION LEGEND**

GW:	GRAVEL, WELL-GRADED
GP:	GRAVEL, POORLY-GRADED
GM:	GRAVEL, SILTY
SW:	SAND, WELL-GRADED
SP:	SAND, POORLY-GRADED
SM:	SAND, SILTY
ML:	SILT
CL:	CLAY, LEAN
OL:	ORGANIC SOIL

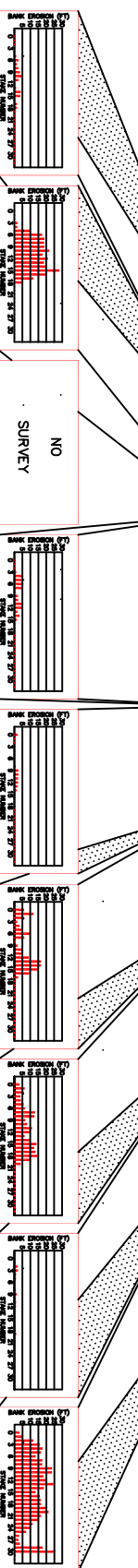
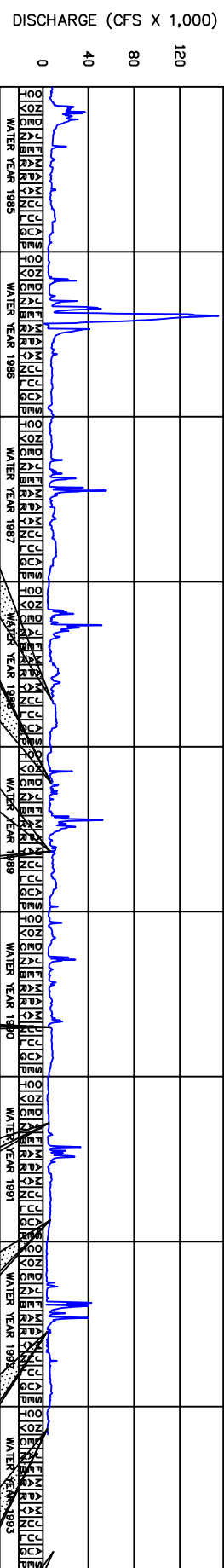
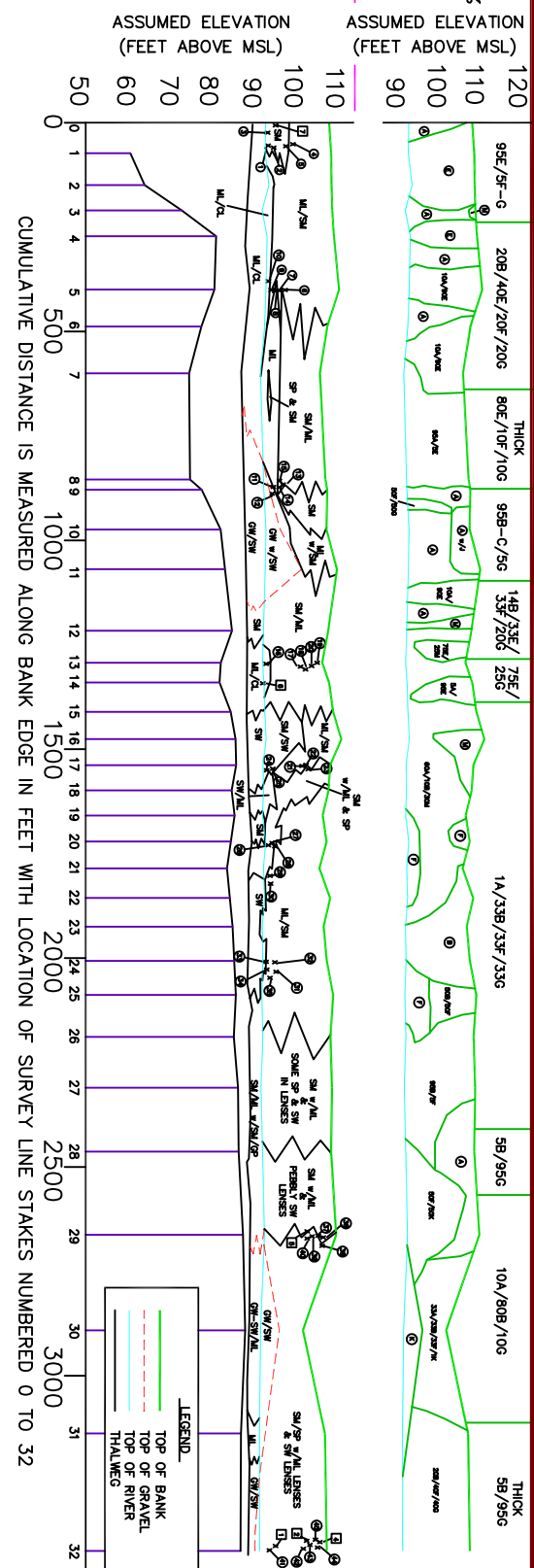
**SAMPLING LOCATIONS LEGEND**

X: EXACT SAMPLE LOCATION  
[1]: SOIL SAMPLE LOCATION  
①: TORVANE/PENETROMETER

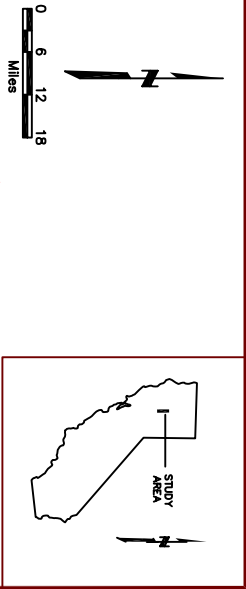
**UNIFIED SOIL CLASSIFICATION LEGEND**

#	T	P	#	T	P	#	T	P	#	T	P
1	3.1	1.50	16	3.1	0.75	31	*	>4.5			
2	2.6	1.25	17	4.1	1.75	32	3.0	0.75			
3	1.8	0.25	18	1.0	0.75	33	0.3	<0.5			
4	5.1	1.50	19	6.4	>4.5	34	4.0	1.50			
5	3.4	1.25	20	0.9	1.00	35	3.4	1.75			
6	3.7	3.25	21	2.4	0.75	36	4.3	>4.5			
7	3.4	1.80	22	2.8	3.00	37	2.8	2.75			
8	2.0	1.25	23	0.4	0.25	38	3.9	>4.5			
9	3.5	1.25	24	4.4	1.25	39	1.9	0.75			
10	2.4	1.00	25	3.4	2.00	40	0.7	0.25			
11	1.9	0.50	26	1.2	0.25	41	2.4	1.50			
12	0.6	0.25	27	1.6	0.50	42	3.9	2.00			
13	4.5	>4.5	28	1.6	0.75	43	1.6	0.75			
14	2.6	4.25	29	4.5	3.25	44	2.6	1.25			
15	1.8	0.50	30	3.9	3.25	45	1.9	1.25			

**PROFILE VIEW OF BANK VEGETATION (TOP) AND BANK SOIL TYPES AND SAMPLING LOCATIONS (BOTTOM)**

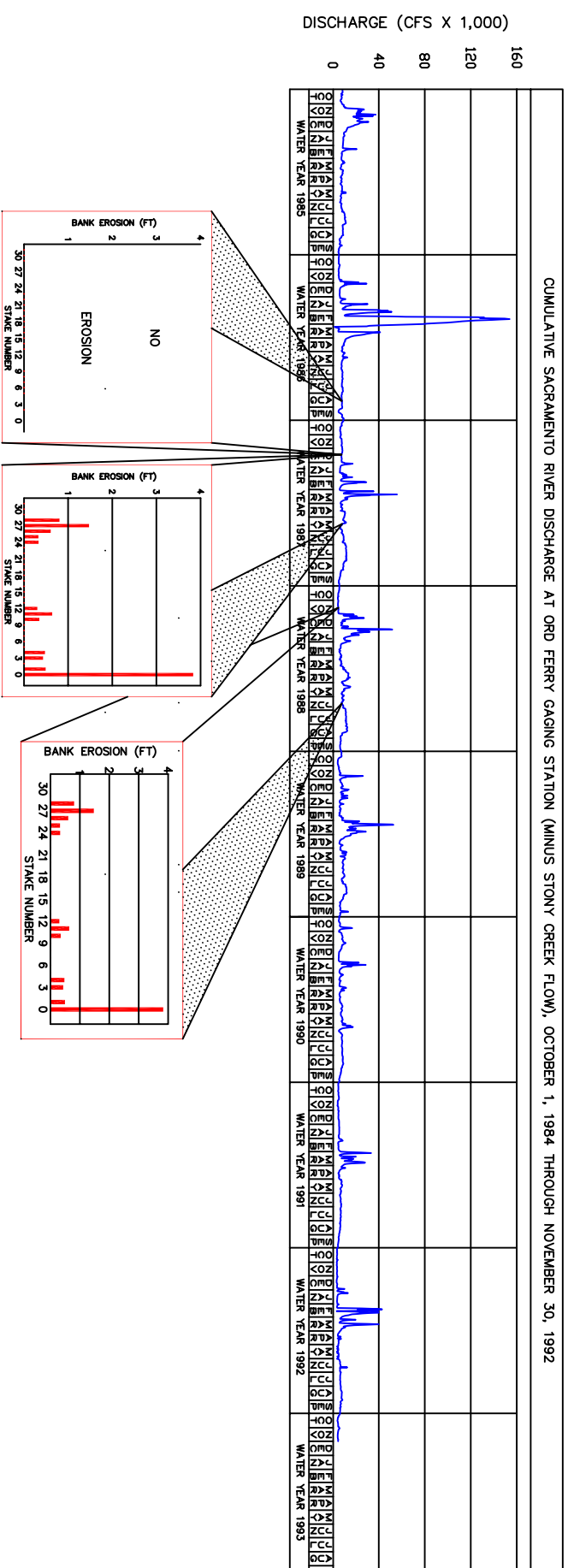
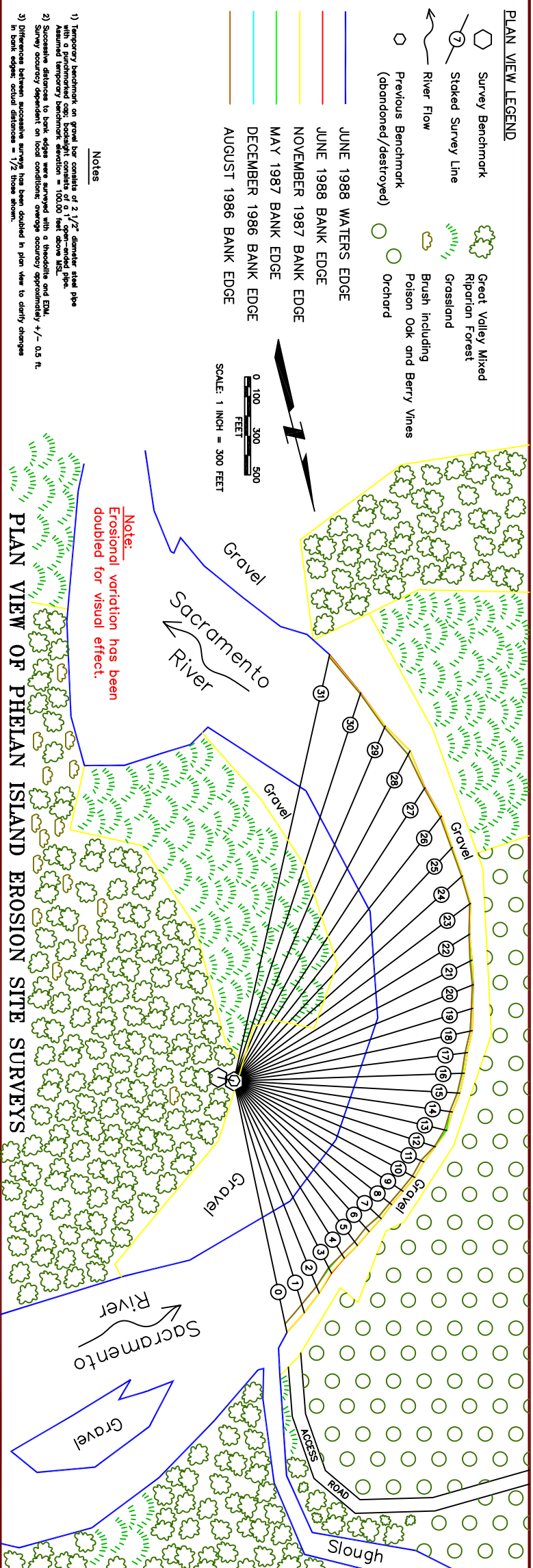


**BANK EROSION RELATIVE TO SACRAMENTO RIVER FLOW AT BIG CHICO CREEK EROSION SITE**

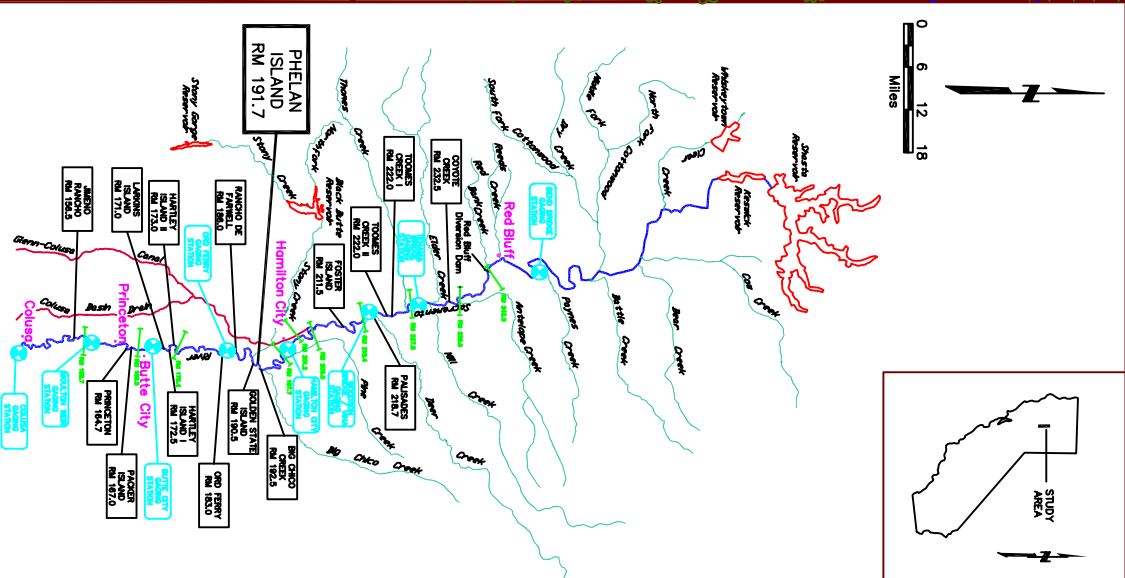


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THE RESOURCES AGENCY  
DEPARTMENT OF WATER RESOURCES  
NORTHERN DISTRICT

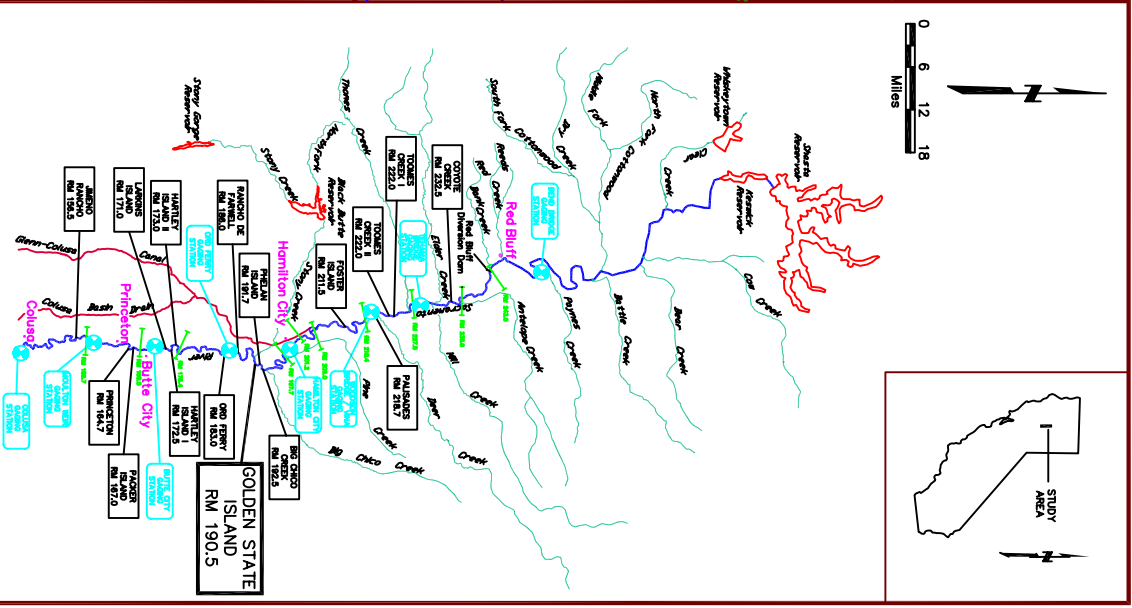
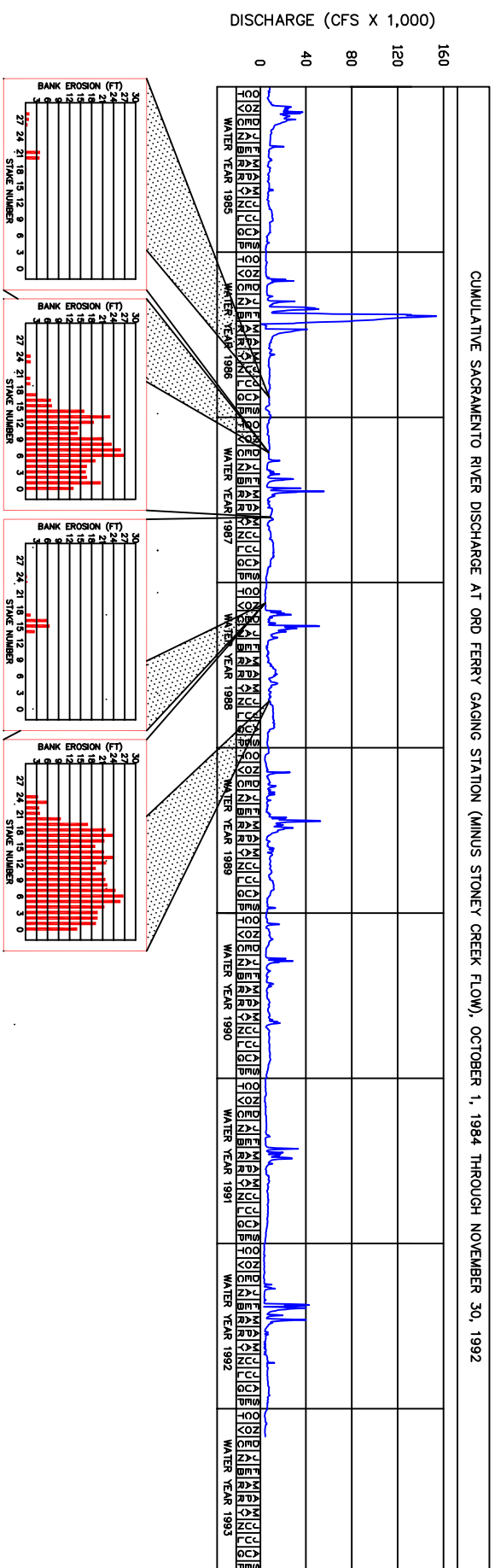
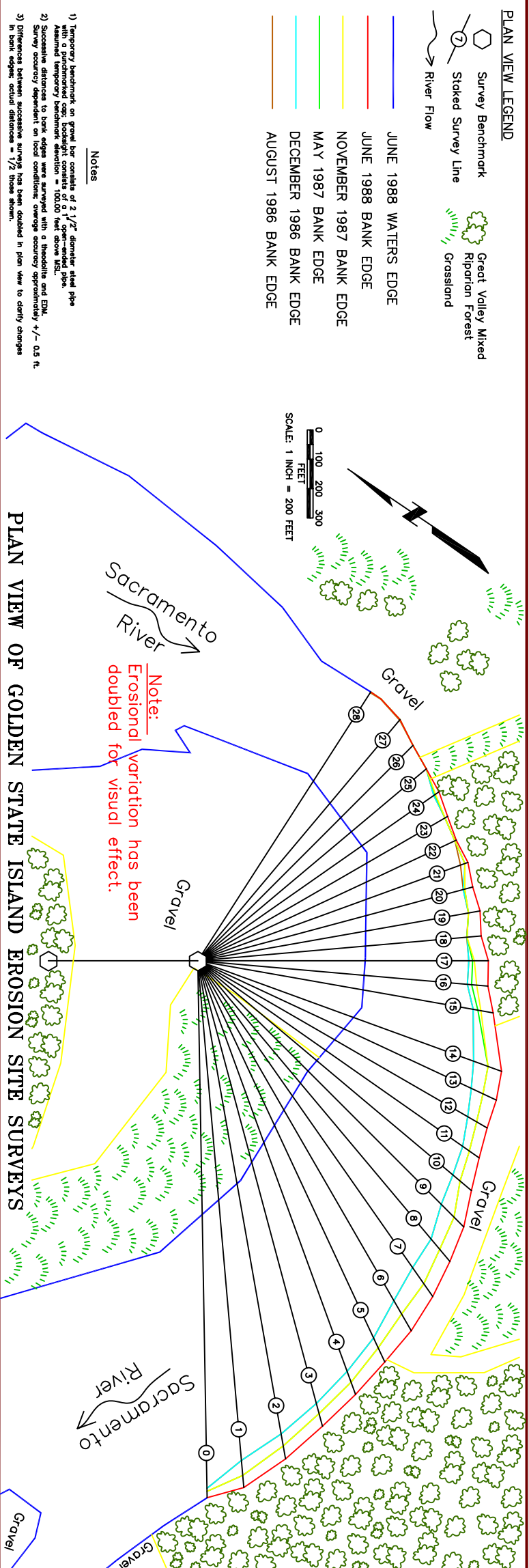
**SACRAMENTO RIVER  
BANK EROSION INVESTIGATION  
BIG CHICO CREEK  
EROSION SITE**

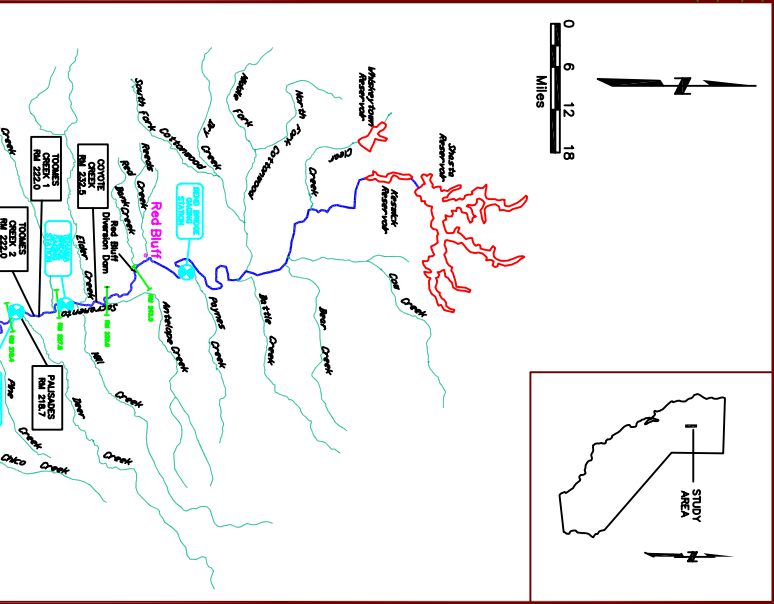
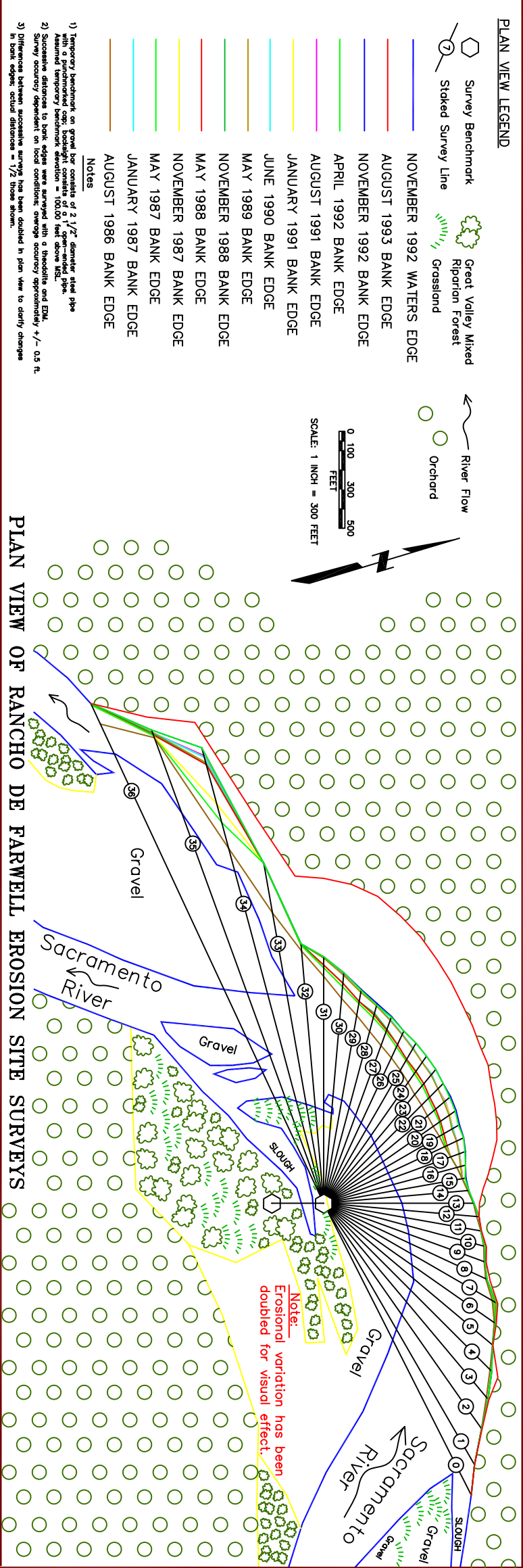


**Note:**  
Site was abandoned after June 1968, when site was rippedraped.







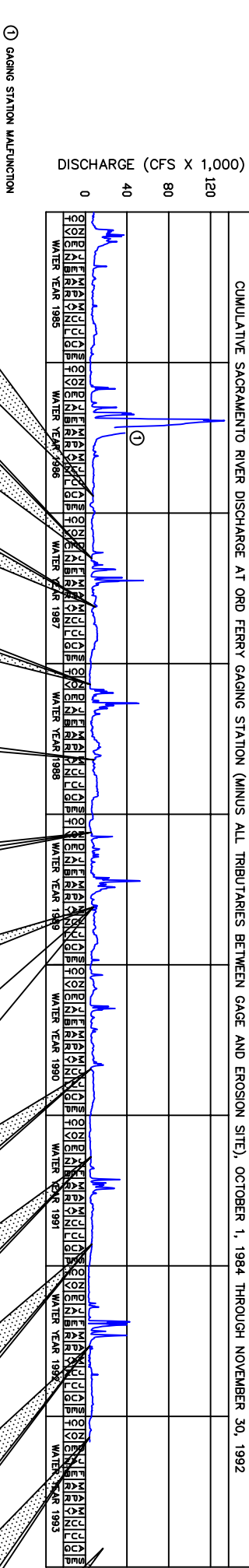
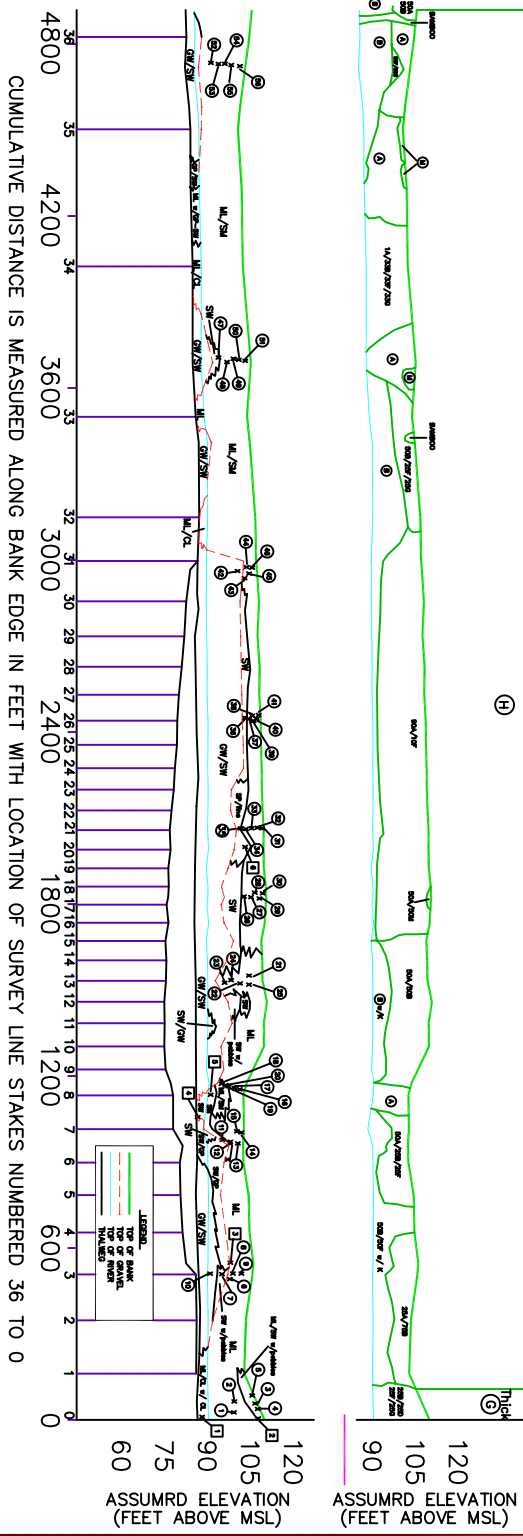


BANK FEATURES PROFILE

- ALL VALUES ARE PERCENTAGES WITH CIRCLES REPRESENTING 100 %
- A: BARE F: SHRUBS K: WILLOWS  
B: GRASS G: TREES M: ROOTS  
D: AQUATIC PLANTS H: ORCHARD

UNIFIED SOIL CLASSIFICATION LEGEND

	#	T	#	T	#	T	#	T	#	T	#	T	P
GW: GRAVEL, WELL-GRADED	1	4.9	4.50	16	3.4	>4.5	31	6.5	>4.5	46	3.1	3.00	
GP: GRAVEL, POORLY-GRADED	2	5.9	4.50	17	5.1	4.00	32	6.1	>4.5	47	1.1	<25	
GM: GRAVEL, SILTY	3	2.3	>4.5	18	3.4	2.00	33	2.8	2.75	48	3.4	2.75	
SW: SAND, WELL-GRADED	4	1.6	4.00	19	4.9	3.25	34	1.9	2.50	49	0.3	0.25	
SP: SAND, POORLY-GRADED	5	1.7	>4.5	20	5.2	3.50	35	1.1	0.75	50	5.2	>4.5	
SM: SAND, SILTY	6	3.6	1.75	21	5.5	>4.5	36	0.6	<25	51	*	>4.5	
ML: SILT	7	*	-	22	4.4	2.50	37	2.4	1.00	52	*	>4.5	
CL: CLAY, LEAN	8	6.3	>4.5	23	2.0	1.50	38	3.9	1.50	53	*	>4.5	
OL: ORGANIC SOIL	9	5.9	>4.5	24	3.7	3.00	39	1.7	0.50	54	*	>4.5	
	10	3.7	1.50	25	4.9	2.50	40	1.6	0.75	55	*	>4.5	
	11	2.4	1.50	26	2.6	1.25	41	6.9	>4.5	56	*	>4.5	
	12	0.7	0.50	27	1.4	0.25	42	0.5	0.25				
X: EXACT SAMPLE LOCATION	13	3.8	>4.5	28	1.9	1.00	43	2.0	1.00				
1: SOIL SAMPLE LOCATION	14	5.1	3.00	29	5.6	3.50	44	1.5	0.75				
1: TORVANE/PENETROMETER	15	4.4	2.75	30	2.9	4.25	45	5.0	1.90				



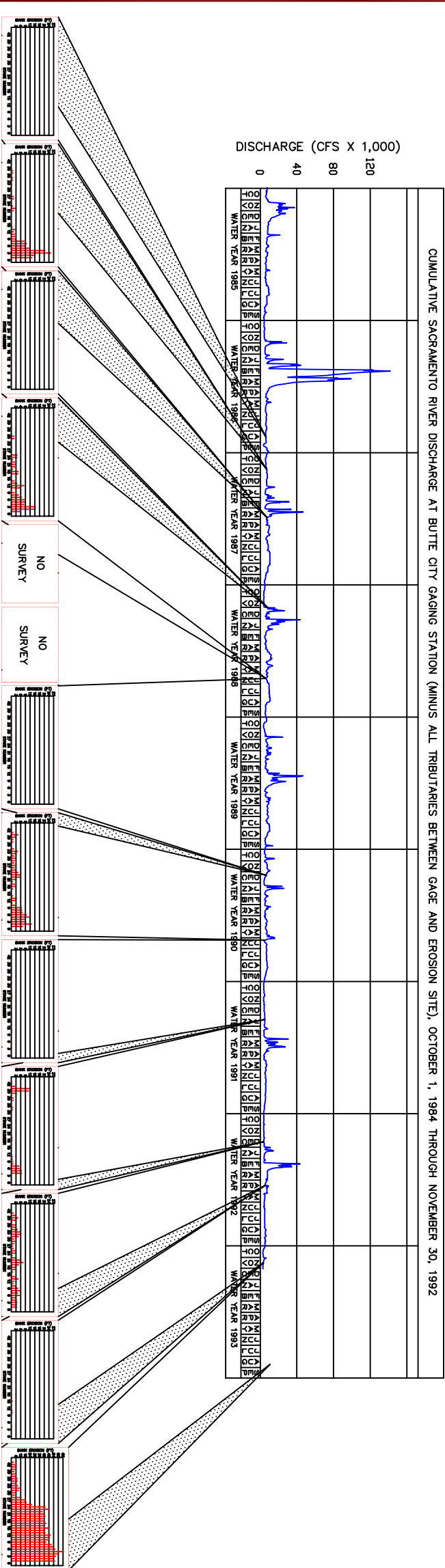
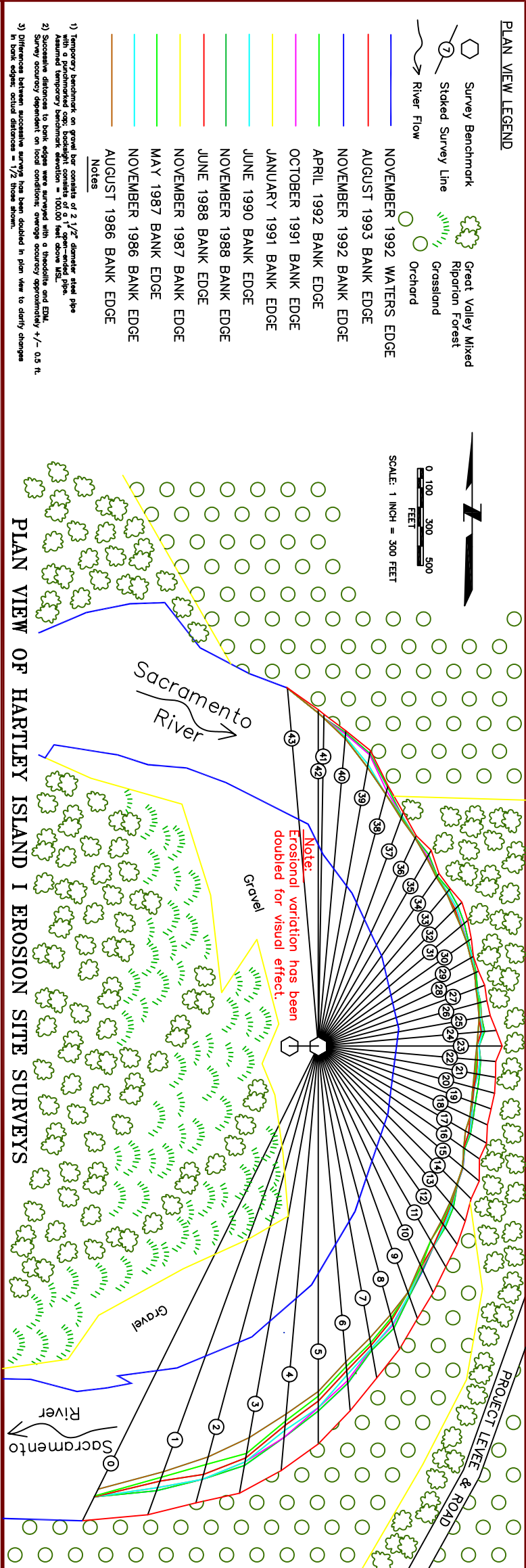
BANK EROSION RELATIVE TO SACRAMENTO RIVER FLOW AT RANCHO DE FARWELL EROSION SITE



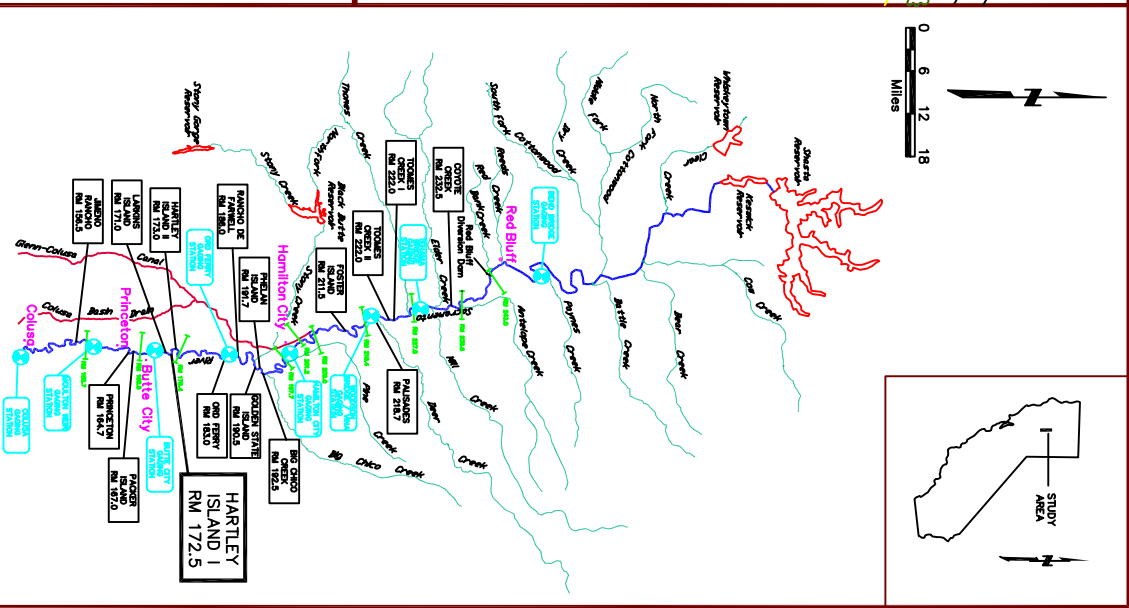




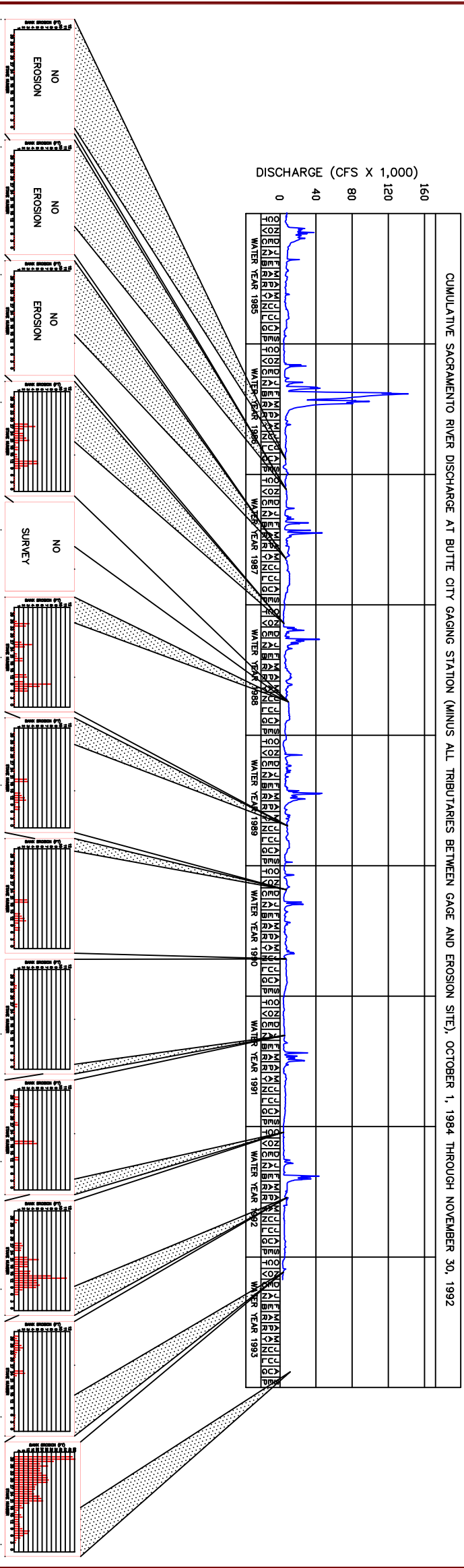
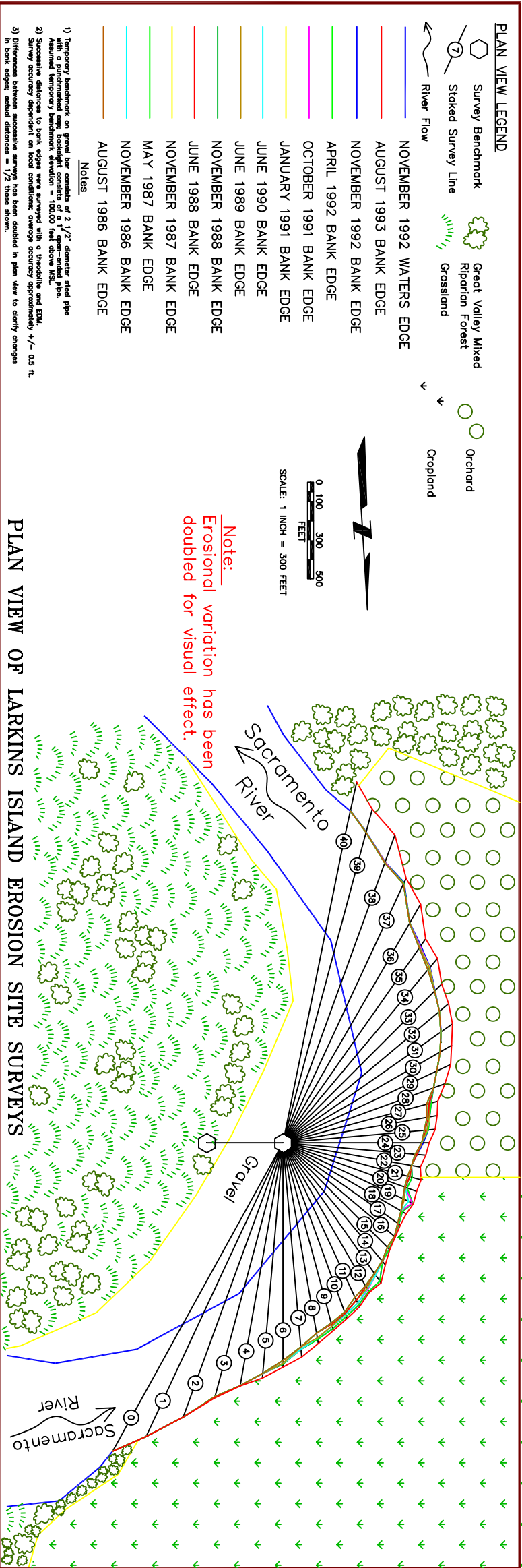




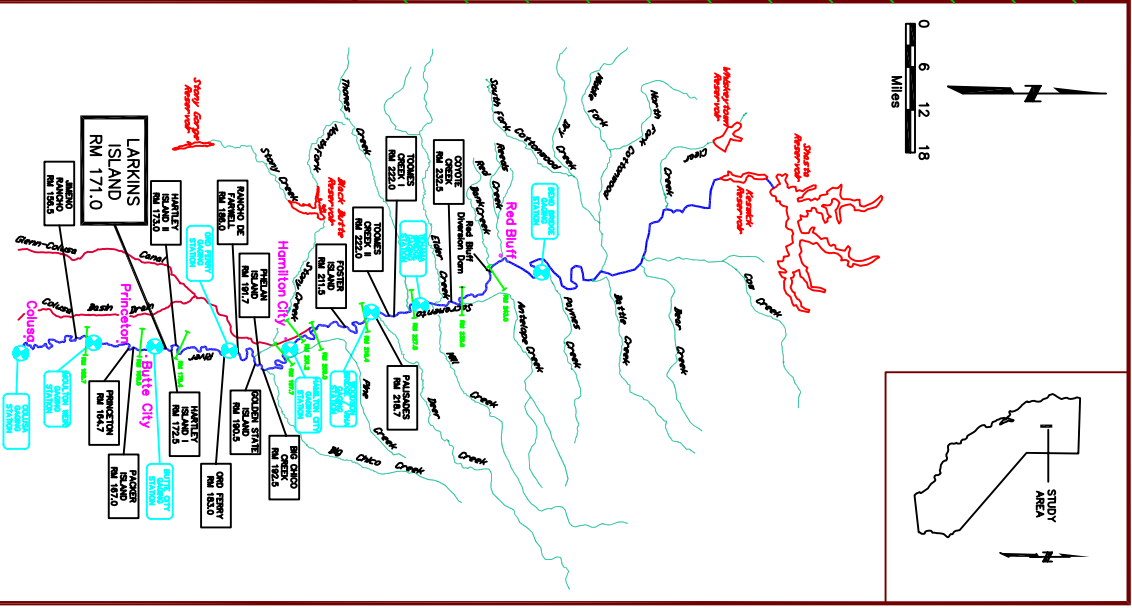
BANK EROSION RELATIVE TO SACRAMENTO RIVER FLOW AT HARTLEY ISLAND I EROSION SITE



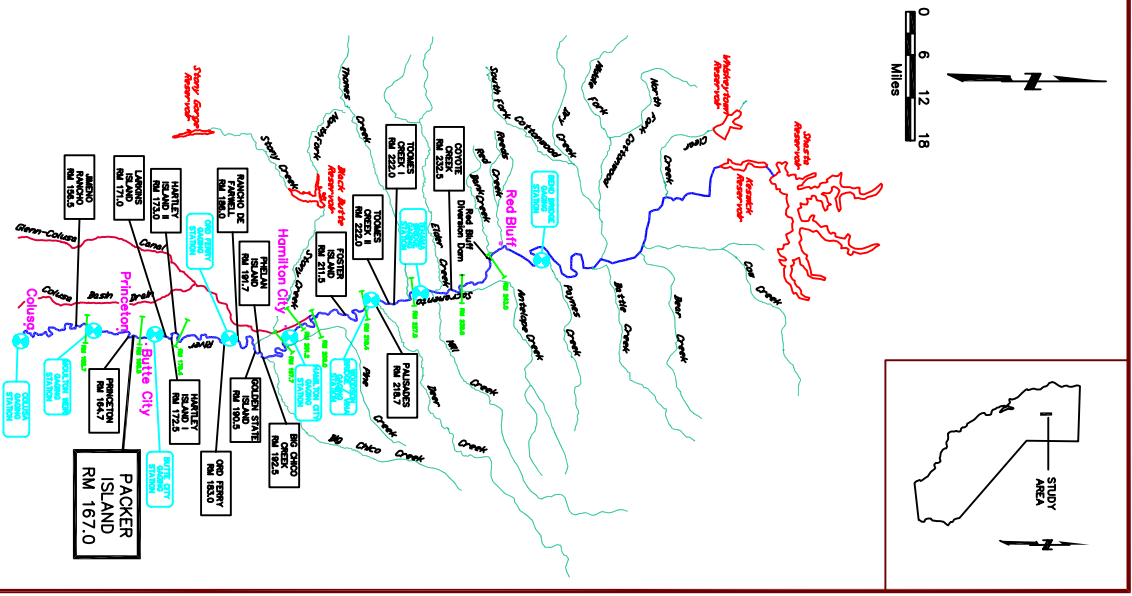
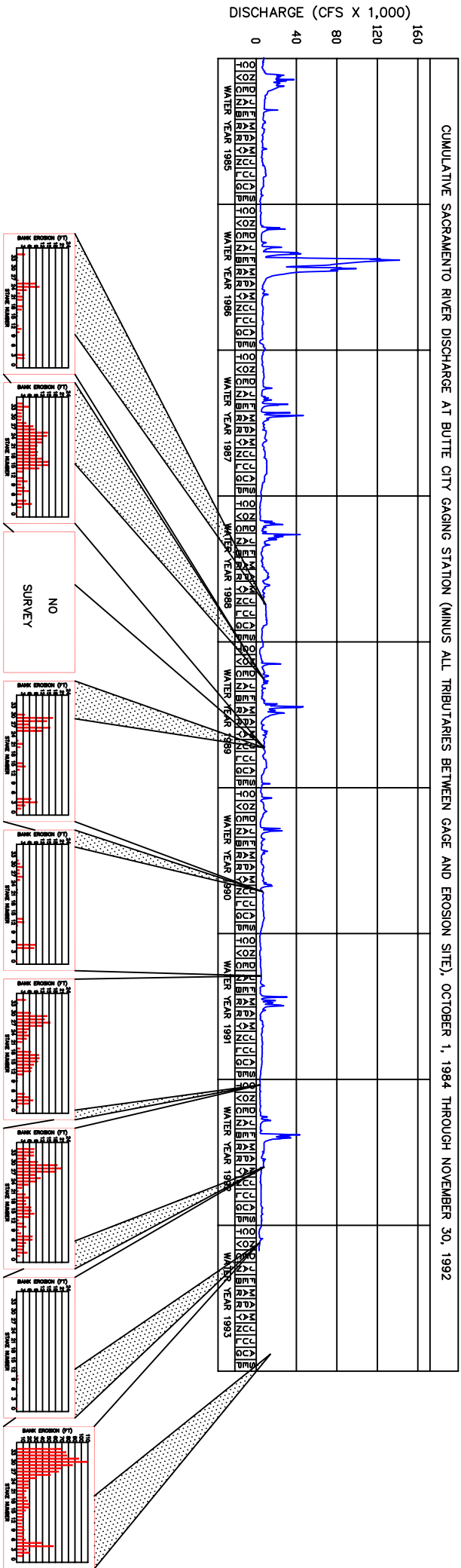
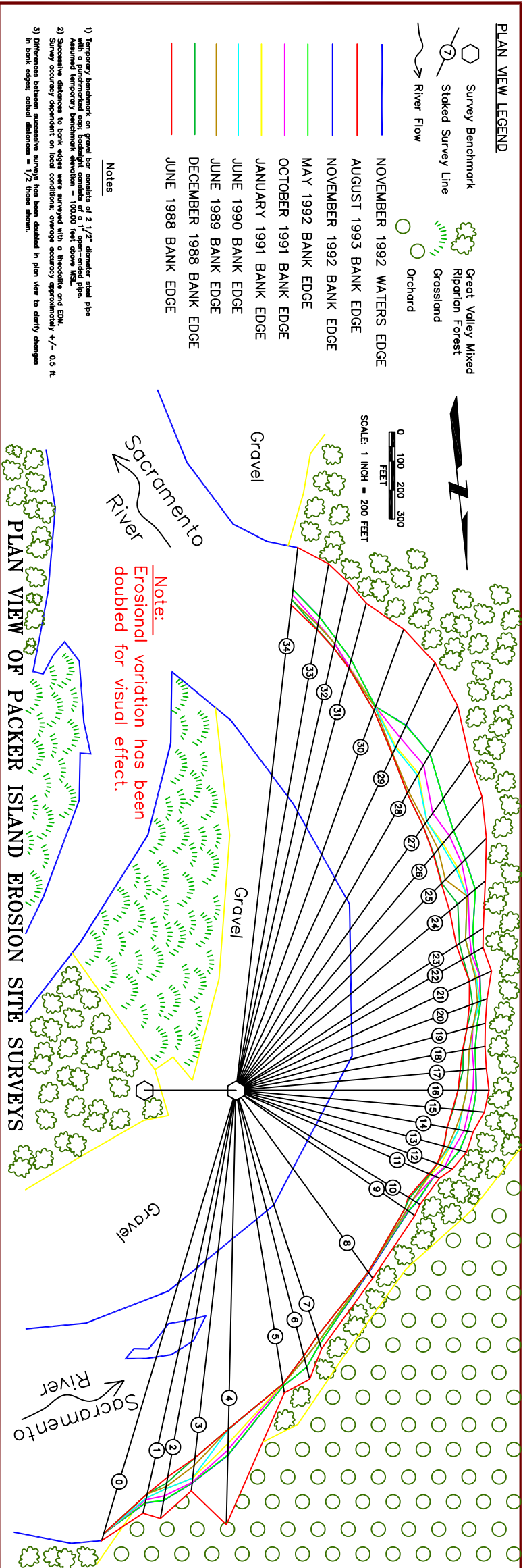




BANK EROSION RELATIVE TO SACRAMENTO RIVER FLOW AT LARKINS ISLAND EROSION SITE

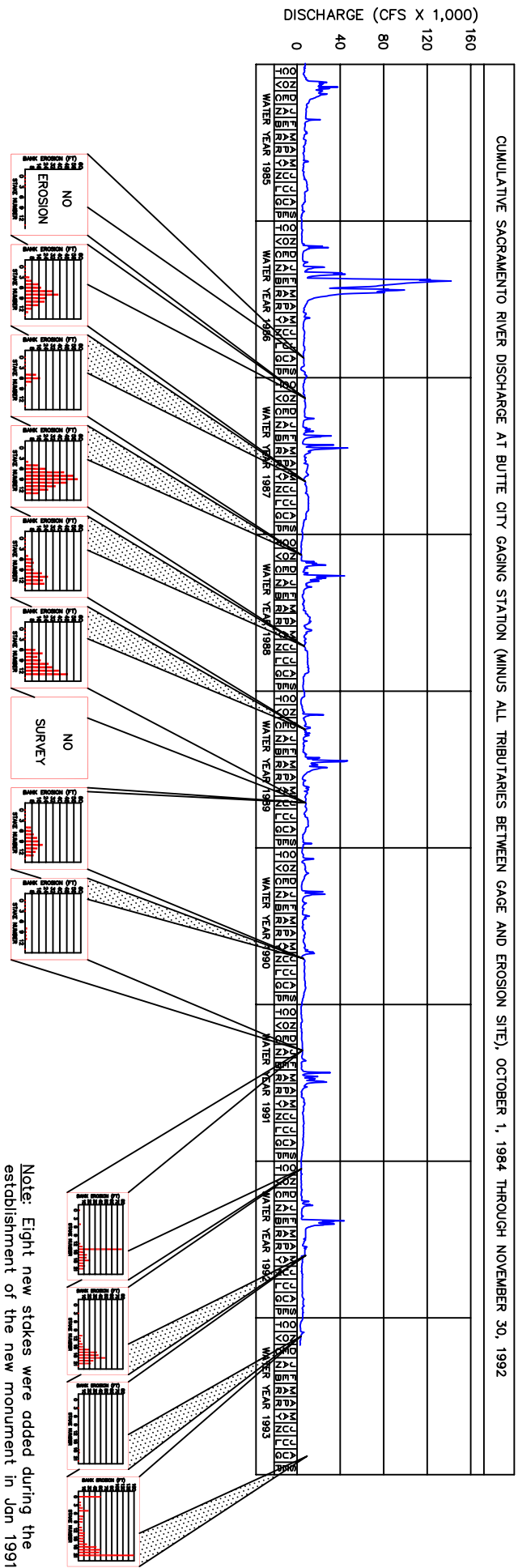
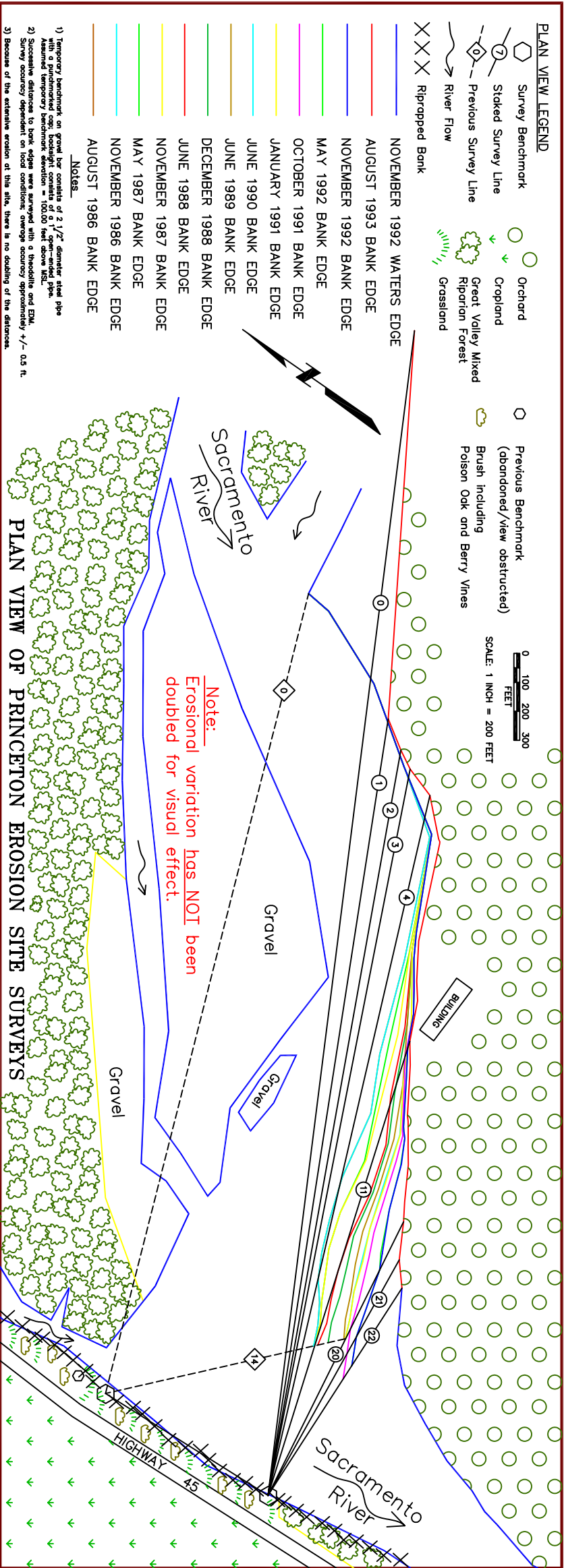


STATE OF CALIFORNIA  
THE RESOURCES AGENCY  
DEPARTMENT OF WATER RESOURCES  
NORTHERN DISTRICT  
SACRAMENTO RIVER  
BANK EROSION INVESTIGATION  
LARKINS ISLAND  
EROSION SITE

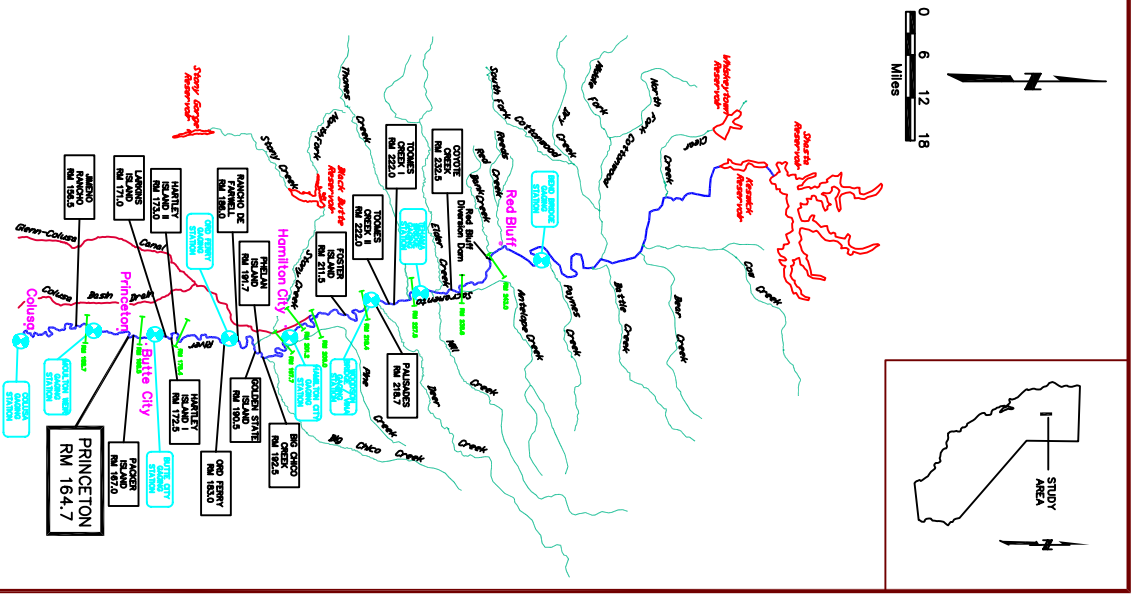


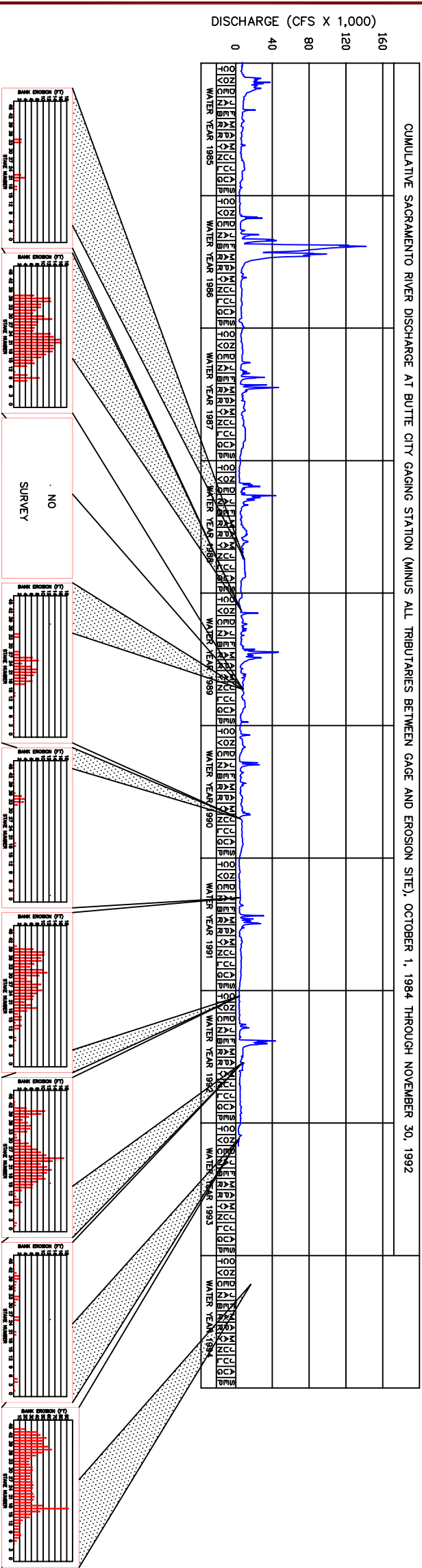
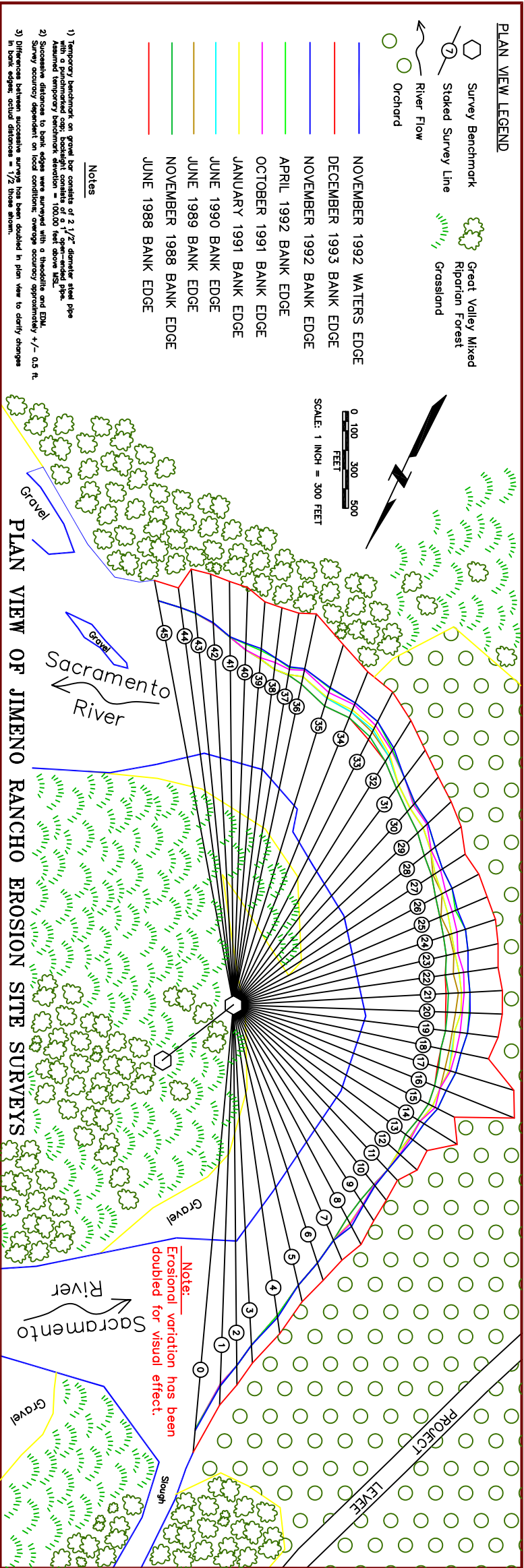
STATE OF CALIFORNIA  
THE RESOURCES AGENCY  
DEPARTMENT OF WATER RESOURCES  
NORTHERN DISTRICT  
SACRAMENTO RIVER  
BANK EROSION INVESTIGATION  
PACKER ISLAND  
EROSION SITE



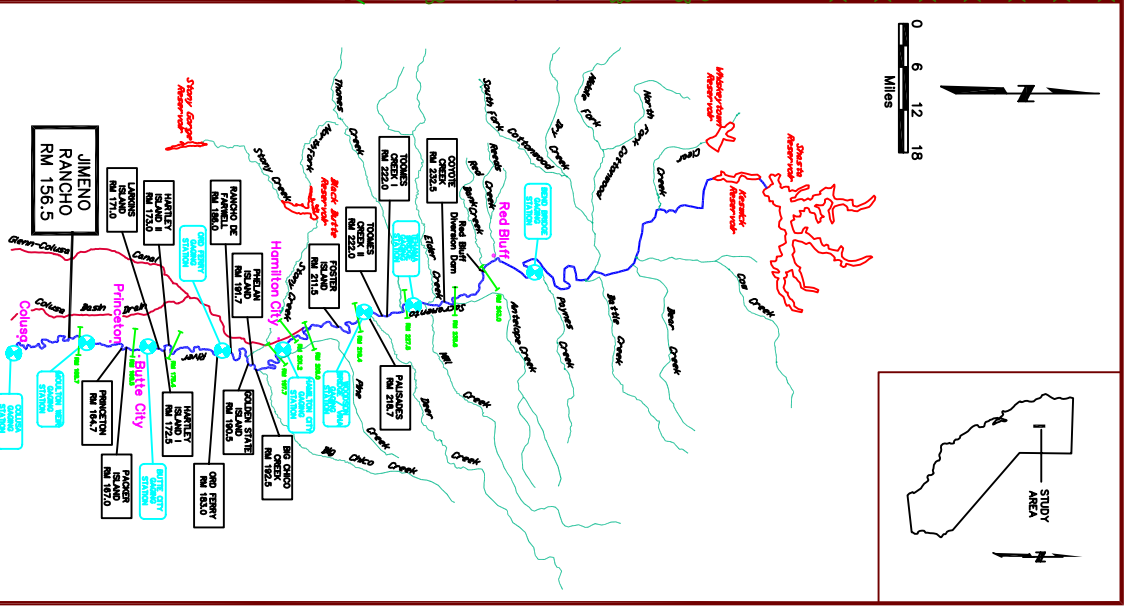


BANK EROSION RELATIVE TO SACRAMENTO RIVER FLOW AT PRINCETON EROSION SITE





BANK EROSION RELATIVE TO SACRAMENTO RIVER FLOW AT JIMENO RANCHO EROSION SITE



STATE OF CALIFORNIA  
THE RESOURCES AGENCY  
DEPARTMENT OF WATER RESOURCES  
NORTHERN DISTRICT

SACRAMENTO RIVER  
BANK EROSION INVESTIGATION  
JIMENO RANCHO  
EROSION SITE